This Chapter is a collection of studies conducted during the 1967 typhoon season. Some topics appear in their entirety. Other topics are of a continuing nature and will be completed when data becomes available.

The following is a list of the topics discussed in this Chapter:

A. A COMPARISON OF OBJECTIVE TECHNIQUES FOR TYPHOON MOVEMENT.

B. A NOTE ON THE STAGE C - "COMMA CONFIGURATION."

C. FORECASTING DEVELOPMENT OF TROPICAL CYCLONES.

D. AN EXAMPLE OF TWO VORTICES WITHIN A LARGE TROPICAL SYSTEM.

E. PRELIMINARY RESULTS OF USING RECONNAISSANCE PERIPHERAL HEIGHT DATA TO FORECAST TYPHOON MOVEMENT.

A. A COMPARISON OF OBJECTIVE TECHNIQUES FOR TYPHOON MOVEMENT

1. Introduction

Few statistics have been compiled concerning the merits of various forecast methods under operational conditions for tropical cyclones in the Pacific. If a number of forecasts are prepared at a given synoptic time using different methods, the Typhoon Duty Officer (TDO) is confronted with a wide divergence of forecast tracks. Unless it is known which technique is superior in a given situation, little or no weight can be given to any of the objective systems. With this in mind, a study was undertaken to evaluate a large number of objective forecasting techniques for tropical cyclones under operational conditions using numerical methods.

Two sets of logs were maintained on all storms. These logs were prepared to facilitate using numbered codes for all entries. The Best Track log was completed following each tropical cyclone, figure III-1A. The Best Track of a cyclone is a post-analyses summary giving cyclone locations, intensities, and directions and speeds of movement. As the various forecasts were made, the 24 Hour Objective Forecast log was filled out by the TDO, figure III-1B. The logs were double checked for accuracy and the data were cut on Hollerith machine cards. The data card information was read into the computer, processed and printed using the online printer.

A simplified flow diagram of the verification program is depicted in figure III-2. The program is such that one or multiple storms may be run at any one time. Examples of the two printouts produced by the program are shown in figure III-3. The first printout, figure III-3A, gives a summary for each individual tropical cyclone. For each individual technique the following information is listed: the verification time, the vector error from the Best Track position to the forecast position, and the average 24 hour forecast error. The second printout, figure III-3B, provides a summary for all the cyclones plus a stratification of the storms by intensity.

To enable a direct comparison of the various objective techniques with the official forecast under operational conditions, the following procedures were incorporated. The verification times were chosen as 0600Z and 1800Z to facilitate using the latest 0000Z and 1200Z upper air charts. Therefore, in terms of upper air charts, a 24 hour forecast is actually a 30 hour forecast. Reconnaissance fixes are normally taken two hours prior to warning time (0400Z, 1000Z, 1600Z and 2200Z). After receipt of the fix at JTWC, this fix position is extrapolated out for a period of two hours. The extrapolated position is then used on the 0000Z, 0600Z, 1200Z and 1800Z warnings. This extrapolated position was also used as a base for the various objective techniques. Therefore, in terms of reconnaissance fixes, a 24 hour forecast is in reality a 26 hour forecast--two hour extrapolation plus the 24 hour objective forecast. All intensities of tropical cyclones were verified (tropical depressions, tropical storms and typhoons).

2. Discussion of Forecast Techniques Tested

A brief summary of the forecasting techniques tested follows and are not listed in order of performance.

a. JTWC - The official Joint Typhoon Warning Central, Guam, forecast. It was used for comparison purposes only.

b. Tse [1] - A method which incorporates the 700 mb synoptic pattern into the forecast scheme. The differences in the 700 mb contour height north-south and east-west are used as the predictors. A nomogram is then entered to give the 24 hour forecast position.

c. Arakawa [2] - The Arakawa technique uses regression equations to forecast 24 and 48 hour movement plus intensities. Using a grid overlay, pressures on the latest surface chart are transferred to a worksheet. Simple computations result in the forecast positions.

d. Climatology - The assumption made using this procedure is that a given storm will move the mean direction and speed of all typhoons that have been located at approximately the same latitude and longitude during that month of previous years. Climatological charts used in this study were compiled by Chin [3] .

e. Extrapolation - Extrapolation is a semi-objective method by which the forecast track is determined using past values of speed, direction and intensity.

f. Monterey 500 mb HAT - Numerical steers obtained from Fleet Numerical Weather Facility (FNWF), Monterey, California, over the computer data line. The program, called HAT, was written by FNWF personnel and uses a grid surrounding the tropical cyclone. The 500 mb barotropic height prognosis is heavily smoothed in the area surrounding the storm. The cyclone is treated as a point vortex and is advected in one hour time steps up to a forecast period of 72 hours.

g. Monterey 1000 mb P - Numerical steers obtained from a program called HATRACK. The program was written by Lcdr. B. L. Bradford and Lt. G. A. Brearton at FNWF and is still considered to be experimental in nature. There are two versions of the program, the first using SR prognostic fields and the second using SR analyses fields. SR fields [4] are constant level data fields in which the small scale disturbances are smoothed out. The storm is advected as a point vortex on the SR field in six hour time steps up to a forecast period of 72 hours. The output steer message gives the following information: (1) name and/or number of the tropical cyclone, (2) date time group of the analysis or forecast field used, (3) time and position of initial request and (4) time, position, and movement vector for each six hour forecast period. A sample output message is shown in figure III-4. Steers were provided at the 1000, 700 and 500 mb levels, however, the program can be modified to use any standard level up to and including 100 mb. The Monterey 1000 mb P technique provides steers using 1000 mb prognostic SR fields.

h. Monterey 700 mb P - Numerical steers using 700 mb prognostic SR fields.

i. Monterey 700 mb A - Same as item "h" except analyses fields are used for the steers.

j. Monterey 700 mb P Modified - A modification of the Monterey 700 mb P technique using history errors. A detailed description of how history errors were applied is contained in part 3.

k. Monterey 500 mb P - Numerical steers using 500 mb prognostic SR fields.

l. Monterey 500 mb A - Same as item "k" except analyses fields are used for the steers.

m. Monterey 500 mb P Modified - A technique similar to item "j" except 500 mb prognostic SR fields are utilized in the steers.

n. Monterey 700 mb A Modified - A method similar to item "j" except analyses rather than prognostic SR fields are used. This technique was used operationally near the end of the typhoon season because of its timeliness. The prognostic SR steers, although resulting in superior forecasts, were often not available unitl after the tropical cyclone warnings were issued.

3. Description of the Monterey SR Modified Technique

In the pursuit of developing a technique for the improvement of the SR forecasts, a method developed by Hardie [5] was tested and with slight modifications was used. In using a history modification, the assumption is made that forecast errors made in the past will continue to occur in the future. The use of a history modification technique is justified in that it corrects for use of the wrong steering level, use of geostrophic rather than actual wind, and errors that have occurred in the prognostic and analyses fields. A vector diagram depicting the modification technique is shown in figure III-5.

4. Testing and Results

The procedures outlined in the previous sections were incorporated to predict the 24 hour movement of the 1967 tropical cyclones in the JTWC area of responsibility. The figures in the tables give average forecast errors in nautical miles and the number of cases used to compute the averages in parenthesis. Direct comparisons between the various forecasting techniques are difficult as the sample size was not homogeneous and the life cycle of the storms tested was not always the same. However, all statistics and comparison figures were made using the same cyclones in the sample. When a specific technique was not doing well in comparison with others, a different technique was substituted in its place, therefore, sample sizes vary considerably. Official forecast verification figures are included in all tables for comparison purposes.

Table III-1A depicts three objective techniques--Tse, Arakawa, and Climatology. The Tse technique, although forecasting direction of movement fairly well, appeared to be consistently slow in speed of movement. The Arakawa forecasts did exceptionally well when the atmosphere was vertically consistent up to 500 mb, however, in cases where vertical consistency did not exist, large forecast errors occurred. Although Climatological forecast errors were larger than any other technique, it still proved to be very useful in the lower latitudes where, frequently, insufficient data was available to use the other techniques to advantage.

Evaluation of the Monterey 500 mb HAT Steers, table III-1B, were discontinued early in the season after ascertaining that the new Monterey HATRACK steers were doing much better in comparison.

Extrapolation, as shown by table III-1C, proved to be one of the best short range forecasting techniques available. However, being a semi-objective method, a direct correlation exists between forecast errors and forecaster experience. In addition, in the Pacific region, upper air measurements are sparse and in many cases non-existent regardless of the geographical location of the tropical cyclone. Therefore, in most cases, "educated" extrapolation will result in superior verifications when compared with other techniques that require accurate upper air analyses.

As was previously mentioned in section 2, in most cases the Monterey SR prognostic steers were not available until after the 06Z and 18Z warnings were issued. The prognostic steers were available for use in issuing the 00Z and 12Z warning, however, verification figures were not made at those times. Verification results of the Monterey prognostic steers, given in table III-1D, indicate that overall, the 700 mb level was the best single steering level by a considerable amount.

A comparison of Monterey steers using analyses versus prognostic fields is shown in table III-1E. the improvement in the forecasts using prognostic over analyses steers was near 17 miles, however the number of cases involved was relatively small.

The application of the history correction as describe in section 3, showed considerable improvement in the Monterey steers. As noted in table III-1F, average errors decreased from 148 to 120 miles for the 700 mb level and 181 to 131 miles for the 500 mb level. It seems reasonable that this type of correction could be applied to other objective forecasting techniques, thereby decreasing forecast errors.

Late in the typhoon season, after determination of the best steering level and how to best apply the history correction, the Monterey 700 mb A Modified technique was tested under operational conditions. Although the number of cases was again relatively small, the results, table III-1G, were comparable in accuracy to the JTWC forecast.

5. <u>Concluding Remarks</u>

Of the 14 tropical cyclone steering methods tested, four showed superior verifications. These were the Monterey 700 mb P Modified, Monterey 700 mb P, extrapolation and Monterey 700 mb A Modified.

If the prognostic SR steers can be made available prior to the issuance of the official warning, they will be of considerable value as an easily used and highly accurate forecasting aid. In addition, use of the history modification technique further reduces the forecast errors by a significant amount. Until such time as prognostic SR steers are available, the history modified analyses SR steers provide one of the best objective forecasting techniques available.

Several limitations of the SR steers were noted during the 1967 season. If the tropical cyclone is of considerable size, greater than 800 miles in diameter, it appears that the SR fields are not sufficiently smoothed. The end result is that the cyclone is steered around its own circulation. A second limitation occurs when the cyclone location is south of 10 degrees north latitude. It is felt that the poor steers resulting in these cases were associated with the treatment of the coriolis parameter in the lower latitudes.

REFERENCES

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3. P. C. Chin, "Tropical Cyclones in the Western Pacific and China Sea from 1884 to 1953", Royal Observatory Hong King, 94 pp.

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BEST TRACK LOG

3	YEAR	36_	36_	36_	36_
2	CYCLONE #	_ _	_ _	_ _	_ _
2	MONTH	_ _	_ _	_ _	_ _
4	DTG	_ _00	_ _06	_ _12	_ _18
3	LATITUDE	_ _ _	_ _ _	_ _ _	_ _ _
3	LONGITUDE	_ _ _	_ _ _	_ _ _	_ _ _
3	DIRECTION OF MVMT	_ _ _	_ _ _	_ _ _	_ _ _
2	SPEED OF MVMT	_ _	_ _	_ _	_ _
3	MAX WND SPEED	_ _ _	_ _ _	_ _ _	_ _ _

A

24 HR OBJECTIVE FORECAST LOG

3	YEAR		56_	56_	56_	56_
2	CYCLONE		_ _	_ _	_ _	_ _
2	MONTH		_ _	_ _	_ _	_ _
4	DTG		_ _06	_ _18	_ _06	_ _18
3	JTWC	LAT	_ _ _	_ _ _	_ _ _	_ _ _
3		LONG	_ _ _	_ _ _	_ _ _	_ _ _
3	TSE	LAT	_ _ _	_ _ _	_ _ _	_ _ _
3		LONG	_ _ _	_ _ _	_ _ _	_ _ _
3	ARAKAWA	LAT	_ _ _	_ _ _	_ _ _	_ _ _
3		LONG	_ _ _	_ _ _	_ _ _	_ _ _
3	CLIMATOLOGY	LAT	_ _ _	_ _ _	_ _ _	_ _ _
3		LONG	_ _ _	_ _ _	_ _ _	_ _ _
3	MTRY 700 PROG M	LAT	_ _ _	_ _ _	_ _ _	_ _ _
3		LONG	_ _ _	_ _ _	_ _ _	_ _ _
3	MTRY 500 ANAL	LAT	_ _ _	_ _ _	_ _ _	_ _ _
3		LONG	_ _ _	_ _ _	_ _ _	_ _ _
3	EXTRAPOLATION	LAT	_ _ _	_ _ _	_ _ _	_ _ _
3		LONG	_ _ _	_ _ _	_ _ _	_ _ _
3	MTRY SFC PROG	LAT	_ _ _	_ _ _	_ _ _	_ _ _
3		LONG	_ _ _	_ _ _	_ _ _	_ _ _
3	MTRY 700 PROG	LAT	_ _ _	_ _ _	_ _ _	_ _ _
3		LONG	_ _ _	_ _ _	_ _ _	_ _ _
3	MTRY 500 PROG	LAT	_ _ _	_ _ _	_ _ _	_ _ _
3		LONG	_ _ _	_ _ _	_ _ _	_ _ _

B

* All fcsts based on 00Z and 12Z charts and extrapolated an additional 6 hrs to conform with our 24 hr fcst.

** All latitudes and longitudes in 10ths of deg.

Figure III-1 JTWC logs

FLOW DIAGRAM FOR 24 HOUR OBJECTIVE TECHNIQUES VERIFICATION PROGRAM

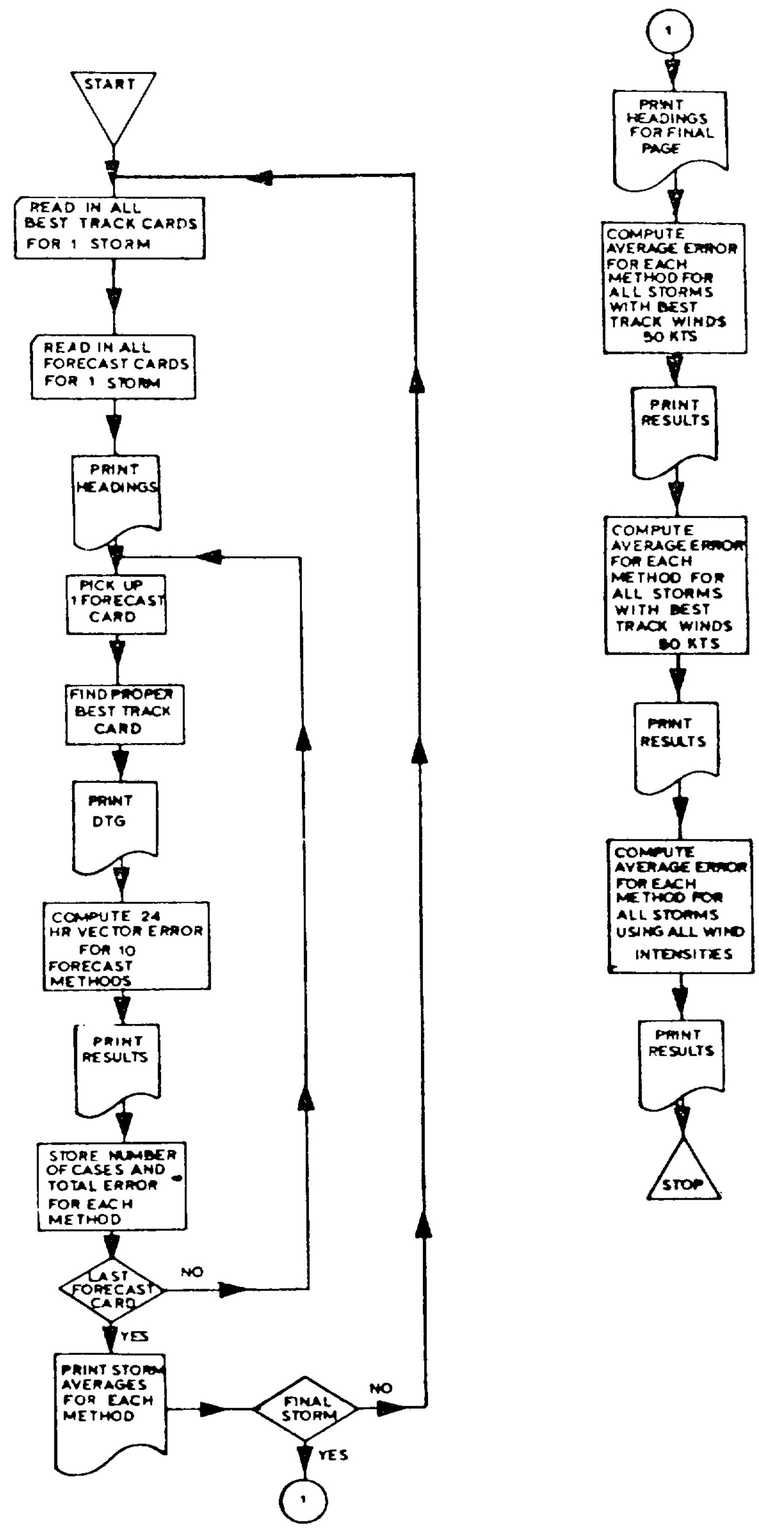


Figure III-2 Computer flow diagram of 24 hour objective techniques verifications program.

24 HOUR OBJECTIVE TECHNIQUES VERIFICATION DATA
TROPICAL CYCLONE 32

DTG	JTWC DEG DIST	MTRY 7 AM DEG DIST	MTRY 5 PM DEG DIST	MTRY 7 A DEG DIST	MTRY 7 PM DEG DIST	MTRY 5 A DEG DIST	EXTRAP DEG DIST	MTRY 1 P DEG DIST	MTRY 7 P DEG DIST	MTRY 5 P DEG DIST
290600Z	267--102	--------	--------	345-- 24	--------	057-- 60	--------	263--132	199-- 36	104-- 90
291800Z	295--192	313--126	277--132	326--108	281--144	060--114	295--192	284--240	281-- 90	064-- 12
300600Z	350--138	347-- 84	052--102	344--132	003--120	--------	357--120	295--318	332--126	068--138
301800Z	018--276	014--102	007--114	355--156	335-- 84	063--192	039--198	299--294	329--162	061--192
010600Z	015-- 72	050-- 54	277-- 48	360-- 48	314-- 24	098-- 78	295--108	290--288	308--102	077--126
011800Z	099--102	110--186	123--108	094--150	121--156	107--240	099--204	266-- 78	110-- 48	097--192
020600Z	078--240	077--150	090--186	076--186	077--150	094--306	078--240	049-- 72	077--[illegible]	093--300
021800Z	090--288	081--150	083--132	079--210	061--144	091--324	078--138	05[illegible]--120	073--156	087--300
030600Z	108--108	086-- 72	019-- 54	078--240	093-- 90	079--270	103--108	081--174	074--223	07[illegible]--270
031800Z	136--138	165--114	153--156	094--210	160--138	096--276	150--180	095--120	089--174	090--270
040600Z	168--144	176-- 96	180-- 54	120--234	205-- 72	115--270	168--144	150--144	116--156	099--270
041800Z	188-- 48	171-- 84	230-- 54	138--198	196-- 42	118--258	234-- 30	178--180	133--144	105--252
050600Z	293-- 54	240--150	258--186	180--204	250--216	146--192	238--234	209--318	186--174	134--168
051800Z	149--102	219--102	174--132	187--258	187--102	152--240	149--102	221--408	196--258	1[illegible]0--234

		MILES
1.	JTWC AVERAGE ERROR ------------------------	143
2.	MTRY 700 ANAL MOD AVERAGE ERROR (OPER) -----	113
3.	MTRY 500 PROG MOD AVERAGE ERROR ------------	112
4.	MTRY 700 ANAL AVERAGE ERROR ----------------	168
5.	MTRY 700 PROG MOD AVERAGE ERROR ------------	114
6.	MTRY 500 ANAL AVERAGE ERROR ----------------	217
7.	EXTRAPOLATION AVERAGE ERROR ----------------	153
8.	MTRY 1000 PROG AVERAGE ERROR ---------------	206
9.	MTRY 700 PROG AVERAGE ERROR ----------------	141
10.	MTRY 500 PROG AVERAGE ERROR ----------------	201

A

OBJECTIVE TECHNIQUES VERIFICATION SUMMARY FOR ENTIRE YEAR

A. MAXIMUM WINDS LESS THAN 50 KNOTS

		MILES	CASES
1.	JTWC AVERAGE ERROR ------------------------	135 --	10
2.	MTRY 700 ANAL MOD AVERAGE ERROR (OPER) ----	130 --	5
3.	MTRY 500 PROG MOD AVERAGE ERROR -----------	117 --	2
4.	MTRY 700 ANAL AVERAGE ERROR ---------------	123 --	8
5.	MTRY 700 PROG MOD AVERAGE ERROR -----------	132 --	2
6.	MTRY 500 ANAL AVERAGE ERROR ---------------	156 --	6
7.	EXTRAPOLATION AVERAGE ERROR ---------------	142 --	8
8.	MTRY 1000 PROG AVERAGE ERROR --------------	185 --	8
9.	MTRY 700 PROG AVERAGE ERROR ---------------	112 --	7
10.	MTRY 500 PROG AVERAGE ERROR ---------------	132 --	7

B. MAXIMUM WINDS 50 KNOTS OR GREATER

		MILES	CASES
1.	JTWC AVERAGE ERROR ------------------------	119 --	76
2.	MTRY 700 ANAL MOD AVERAGE ERROR (OPER) ----	133 --	72
3.	MTRY 500 PROG MOD AVERAGE ERROR -----------	144 --	47
4.	MTRY 700 ANAL AVERAGE ERROR ---------------	157 --	68
5.	MTRY 700 PROG MOD AVERAGE ERROR -----------	124 --	47
6.	MTRY 500 ANAL AVERAGE ERROR ---------------	203 --	67
7.	EXTRAPOLATION AVERAGE ERROR ---------------	135 --	67
8.	MTRY 1000 PROG AVERAGE ERROR --------------	178 --	54
9.	MTRY 700 PROG AVERAGE ERROR ---------------	140 --	59
10.	MTRY 500 PROG AVERAGE ERROR ---------------	187 --	58

C. AVERAGE FOR ALL WIND INTENSITIES

		MILES	CASES
1.	JTWC AVERAGE ERROR ------------------------	121 --	86
2.	MTRY 700 ANAL MOD AVERAGE ERROR (OPER) ----	133 --	77
3.	MTRY 500 PROG MOD AVERAGE ERROR -----------	143 --	49
4.	MTRY 700 ANAL AVERAGE ERROR ---------------	153 --	76
5.	MTRY 700 PROG MOD AVERAGE ERROR -----------	124 --	49
6.	MTRY 500 ANAL AVERAGE ERROR ---------------	199 --	73
7.	EXTRAPOLATION AVERAGE ERROR ---------------	136 --	75
8.	MTRY 1000 PROG AVERAGE ERROR --------------	179 --	62
9.	MTRY 700 PROG AVERAGE ERROR ---------------	137 --	66
10.	MTRY 500 PROG AVERAGE ERROR ---------------	181 --	65

B

Figure III-3 24 hour objective techniques verification program printouts.

FM COMPUTER CNTR

TO JTWC

TROPICAL CYCLONE STEERING

EXPERIMENTAL ANAL

G39 GILDA

ANAL TIME 00181167

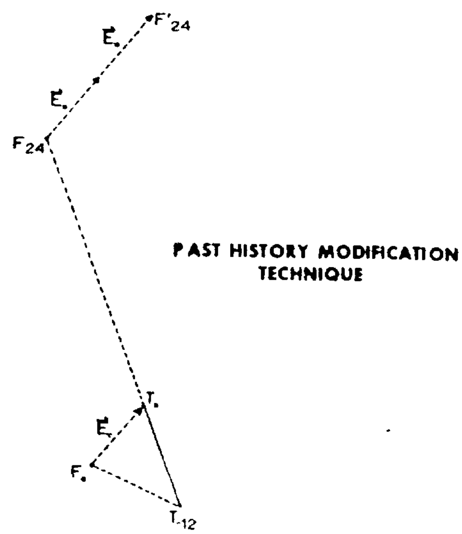
LEVEL 700MBS

12181167	243N	1207E	3604
18181167	248N	1206E	0004
00191167	253N	1207E	0104
06191167	258N	1208E	0204
12191167	263N	1210E	0204
18191167	268N	1212E	0306
00201167	273N	1216E	0306
06201167	279N	1220E	0406
12201167	285N	1225E	0408
18201167	291N	1231E	0508
00211167	297N	1238E	0508

LEVEL 500MBS

12181167	243N	1207E	0615
18181167	250N	1221E	0715
00191167	257N	1238E	0717
06191167	263N	1257E	0719
12191167	270N	1278E	0721
18191167	276N	1301E	0823
00201167	280N	1328E	0925
06201167	282N	1356E	0927
12201167	280N	1387E	1029
18201167	278N	1420E	1031
00211167	272N	1455E	1033

Figure III-4 Monterey computer steer message.



T_o= Present position of storm from latest JTWC warning

T_{-12}= Position of storm 12 hours previous from reconnaissance reports

F_o= Forecast position of storm from position T_{-12}

E_o= Vector error for previous 12 hour forecast

F_{24}= 24 hour forecast position from T_o

F'_{24}= 24 hour forecast position of storm with 2 times the past 12 hour vector error applied

Figure III-5 24 hour history modification technique.

Tse, Arakawa and Climatology

	Official	166	(193)
	Tse	189	(189)
	Arakawa	198	(155)
A	Climatology	212	(149)

Monterey 500 MB Hat

	Official	1[illegible]	([illegible]5)
B	Monterey 500 mb Hat	1[illegible]	([illegible]0)

Extrapolation

	Official	152	(279)
C	Extrapolation	151	(268)

Monterey Prognostic (P) Steers

	Official	159	(234)
	Monterey 1000 mb P	192	(210)
	Monterey 700 mb P	153	(209)
D	Monterey 500 mb P	173	(200)

Monterey 700 MB and 500 MB Anal (A) Steers
vs
Monterey 700 MB and 500 MB Prog (P) Steers

	Official	121	(86)
	Monterey 700 mb A	153	(76)
	Monterey 700 mb P	137	(66)
	Monterey 500 mb A	199	(73)
E	Monterey 500 mb P	181	(65)

Monterey 700 MB and 500 MB Prog (P) Steers
vs
Monterey 700 MB and 500 MB Prog (P) Modified Steers

	Official	153	(173)
	Monterey 700 mb P	148	(163)
	Monterey 700 mb P Modified	120	(128)
	Monterey 500 mb P	181	(160)
F	Monterey 500 mb P Modified	131	(128)

Monterey 700 MB Anal (A) Steers
vs
Monterey 700MB Anal (A) Modified Steers

	Official	118	(75)
	Monterey 700 mb A	154	(65)
G	Monterey 700 mb A Modified	126	(65)

Table III-1 24 hour objective techniques verification figures.

B. A NOTE ON THE STAGE C - "COMMA CONFIGURATION"

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Andersen AFB, Guam, Mariana Islands

Numerous examples have been collected which testify to the general validity of the model of tropical cyclone formation described by the author in 1964 [1] . (See figure III-6). Two examples showing a Stage B and a Stage C "Comma Configuration" are displayed in figures III-7 and III-8 respectively. Maximum wind speeds reported for the Stage B depression in the Gulf of Mexico were 20 knots and for the formative stage of Marie shown in figure III-8 reported values of 30 knots were obtained. These values are in excellent agreement with the model shown in figure III-6.

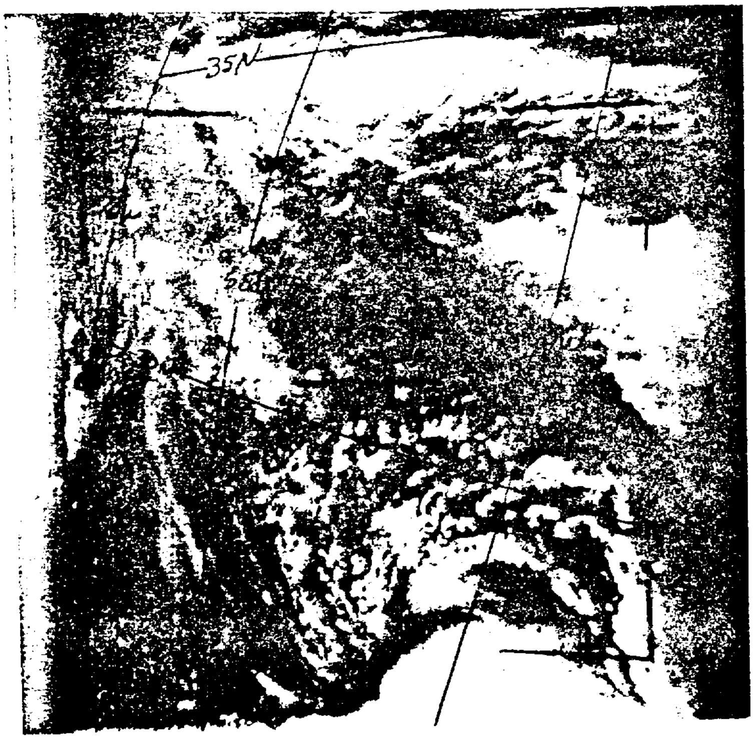
In figure III-9 an example of a storm which does not fit the model is shown. Pronounced banding of low cloudiness north of the major overcast area suggests a center of circulation very near 27.8N and 60.3W. This position is on the edge of the bright overcast cloudiness. The center is embedded by less than 1/2 degree within the overcast cloudiness and hence the storm cannot be classified as to intensity according to the scheme of Timchalk, Hubert and Fritz [2] . The storm can be classified as an intense example of a Stage C+ "Comma Configuration". However, maximum wind speed reported by reconnaissance within one hour of the pictures was 70 knots, a value not at all in keeping with the storm's apparent formative structure.

A few examples of similar storms with unusually high winds have been noted during the past several years of satellite observations. Until now these storms have been considered oddities and no explanation has been suggested to account for the deviation from the normal pattern.

On the 5th of July 1967 the author flew a reconnaissance mission into what was thought to be a formative tropical cyclone. ESSA II pictures of the storm (Billie) on July 4, 1967 at 2320 GMT are shown in figure III-10. The center of circulation of the storm is apparent on the north side of overcast cloudiness near 16.5N, 128E. The storm has the appearance of a Stage C, Comma Configuration and therefore maximum winds of about 30 knots were anticipated. Instead, as the aircraft approached the center, wind speeds of 70 to 80 knots were suddenly encountered. The "eye" of the storm was formed by swirling masses of flattened cumulus and stratocumulus. A picture of the eye taken by the author on 5 July at 0330 GMT is shown in figure III-11. The aircraft's altitude was 10,200 feet. Tops of these clouds were about 4,000 feet. In the area of the eye, no higher cloudiness and certainly no wall cloud in the conventional sense existed. All convective cloudiness of importance lay at least 30 miles to the south of the storm's center. Yet the storm had a very definite warm core. On the first penetration on July 4th at 2120 GMT, temperatures at the 726 mb level rose from values of 14.1°C a few miles away from the eye to a value of 17.2°C directly over the eye. On the second penetration on July 5th at 0330 GMT at 700 mbs temperature rose from values of 13.5°C a few miles outside of the eye to a value of 18.5°C directly over the eye. The temperature rises were noted as the aircraft flew over the eye in perfectly clear, cloud-free conditions. This, then was the key to an understanding of why the storm was so intense. Somehow it had become "warm-core" without ever developing a wall-cloud. Turning back to figure III-9 it can be seen that the eye of this storm was also apparently formed only by low cloudiness. Note the shadow of upper-cloudiness falling on the low clouds which swirl about the eye.

How can a warm core be established in a storm which does not have a wall-cloud? The obvious answer is through forced descent of upper-tropospheric air into the storm's center, resulting in warming through compression. The storm could not have become warm core through ascending motion and release of latent heat near the eye. Any upward motion in such a moist environment would surely have produced significant cloudiness of great vertical development and this was not observed. On the contrary, low cloudiness present was flattened and suppressed. What mechanism could cause forced descent of upper tropospheric air into the narrow region around the eye? A most probable answer is low level divergence. If the winds about the storm center (which we may assume was initially cold core) were through some mechanism to become super-gradient, then cyclonic outflow and evacuation of air would occur from the storm center at low levels. Descending air from higher levels would be required by continuity followed by warming through compression. A lowering of pressure would occur because of the warming and the pressure gradient force into the storm center would be increased. Winds now swirling about the storm center would suddenly become sub-gradient and converge toward the storm center. But by conservation of angular momentum as they converged toward the center their speeds would increase until they were again super-gradient. In this manner pulsating between super-gradient and sub-gradient wind speeds would gradually increase until some upper limit was reached and steady state attained. Based on the sample of storms viewed over the past several years including three storms similar to Billie which the author has flown into, this upper limit appears to be about 70 to 80 knots. Storms of greater intensity invariably have a wall-cloud over a large segment around the eye.

It is easily seen why storms which do have a wall-cloud can become more intense. The upper limit in a storm of the Billie variety is necessarily prescribed by the temperature of the undisturbed high level tropospheric air drawn down into the eye. Higher temperatures in storms with wall-clouds must be attributed to forced warming of air already



T7 6610/6609 8 SEP 1964 1112Z

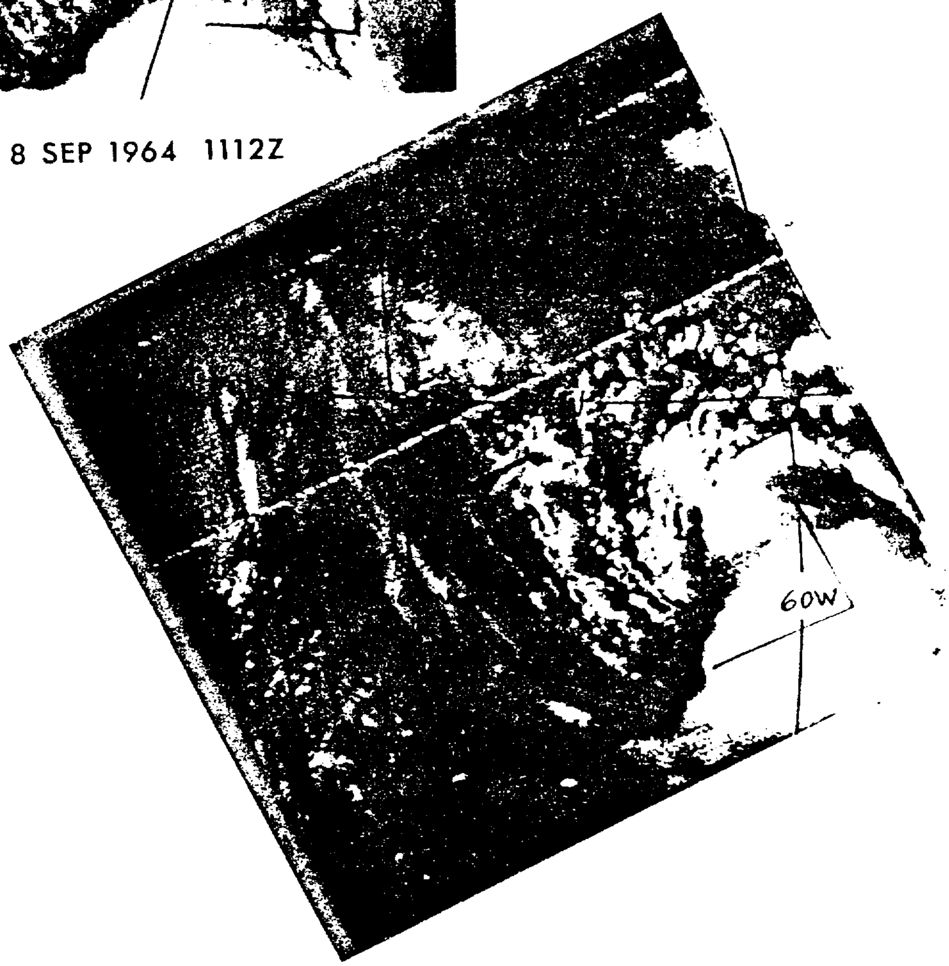


Figure III-9

Figure III-10

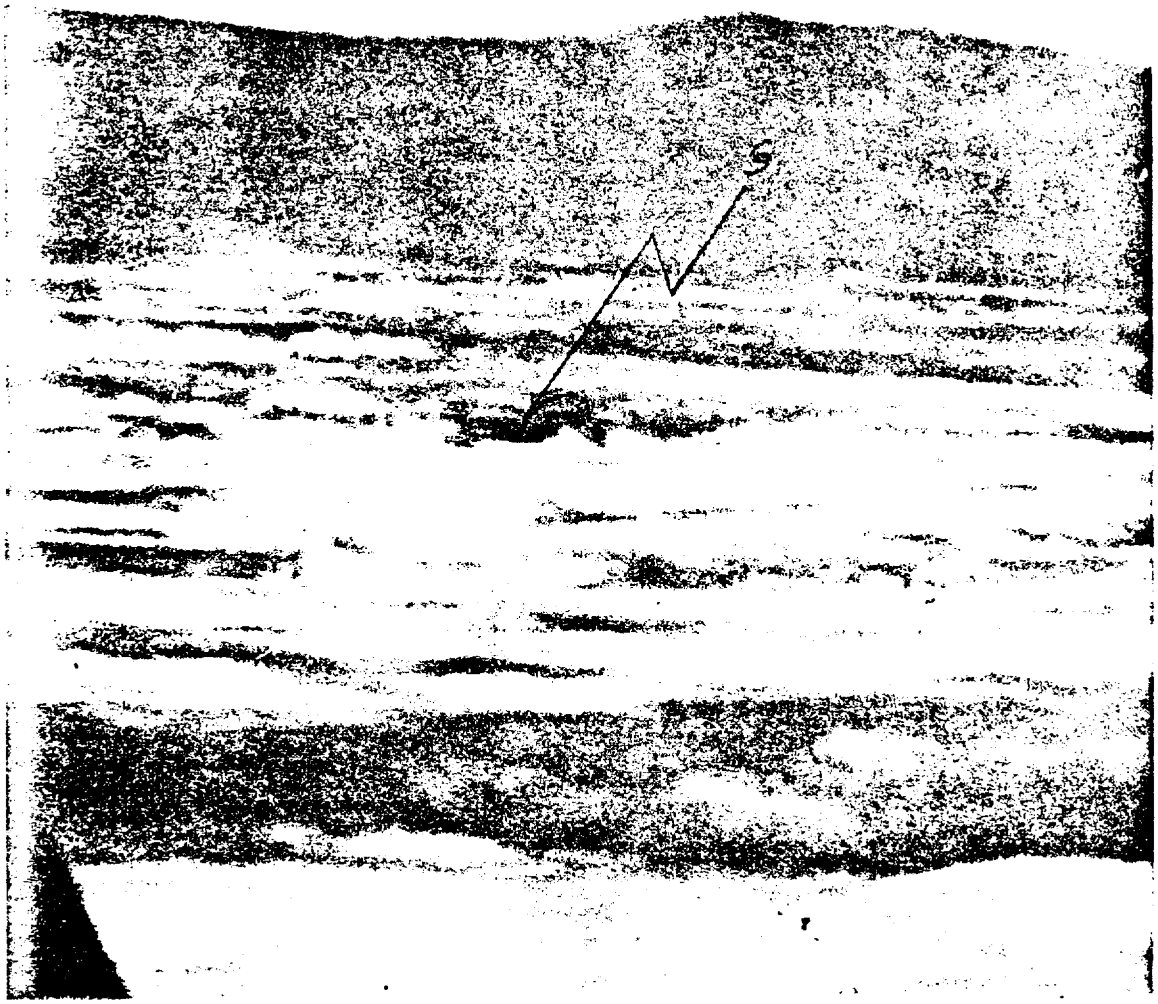


Figure III-11

C. FORECASTING DEVELOPMENT OF TROPICAL CYCLONES

A method to forecast formation of Tropical Cyclones was formulated using conventional synoptic data and local APT cloud pictures. 200 mb synoptic data were used to determine potential development 72 hours in advance and surface and 700 mb data were used to forecast development in 48 hours or less. The four basic types of formation in this method are:

1. Type 1A: Vortex in the Intertropical Convergence Zone (ITC) or in the basic easterly low level wind flow during the summer.

2. Type 1B: Vortex in the low level southwesterly monsoon during summer.

3. Type 2: Vortex embedded in the basic southerly low level "feeding" into another storm, during summer.

4. Type 3: Vortex in the ITC or in the basic easterly low level wind flow during winter.

The following methods were used to forecast formation.

1. 72 hour outlook:

   a. If Mid-Pacific Trough or other major troughs at 200 mbs are absent west of 175E: Typhoon formation unlikely: Only type 1B in the South China Sea and type 2 which is relatively rare should occur.

   b. If Mid-Pacific Trough is present north of 15N, Type 1A formation possible during summer in an area between 25N - 15N and 135E - 170E.

   c. If Mid-Pacific Trough is present south of 15N, Type 1A formation possible during summer in an area between 15N - Equator and 135E - 175E. Type 3 formation possible during winter in an area between 10N - Equator and 135E - 160E.

2. 24 to 48 hour forecast:

   a. Inspect current surface streamline analysis and locate lows of the 4 types:

      (1). During summer:

         (a). Type 1A vortex embedded in the easterlies south of 15N.

(b). Type 1B (in the South China Sea) vortex embedded in the low level southwest monsoon flow with easterlies to the north of it.

(c). Type 2 vortex to the east or south of a typhoon.

(2). During winter:

(a). Type 3 vortex embedded in the easterlies south of 10N with the following synoptic pattern.

/1/. Veering of wind at nearby island station.

/2/. Cyclonic turning of wind flow into southern hemisphere.

/3/. Shearline approaching vortex from the northwest.

b. Inspect current 700 mb streamline analysis and locate lows of the 4 types:

(1). During summer:

(a). Type 1A vortex south of 15N in the easterly flow.

(b). Type 1B (in the South China Sea) vortex present if Clark AFB, Philippine's wind is southerly and Vietnam's wind is northerly or westerly.

(c). Type 2 low to east or south of a typhoon.

(2). During winter:

(a). Type 3 low south of 10N with trough oriented east-west slightly north of the equator.

(b). Tropical depression not possible if low clouds are absent.

c. Inspect current APT cloud pictures.

(1). If there are no significant overcast cloud systems south of 25N, no Tropical Depression possible.

(2). During summer, with a surface and 700 mb low present, the cloud pictures will verify the existence of a low and show its stage of development. The four cloud pictures (figures III-12 through III-15) illustrate the important features to observe.

In summary, this article is not all conclusive for forecasting tropical cyclone development. Other types exist, however, the four types discussed above were the ones most frequently observed during the 1967 season.

Figure III-12

TYPE 1A:
1. Almost circular overcast cloud mass (core).
2. Major overcast cloud mass (bands) located south of center.
3. Cloud bands turning cyclonically into overcast cloud mass.
4. Cirrus blow-off from tops of overcast clouds.

Figure III-13

TYPE 1B in the South China Sea:
1. Cloud bands oriented parallel to the southwest monsoon flow.
2. Small central overcast cloud mass (core).
3. Cyclonic turning of cloud bands into overcast mass.
4. Cirrus blow-off towards west.

Figure III-14

TYPE 2:

1. Cut-off overcast cloud mass (core) from the southerly low level wind flow into another storm to north or west.
2. Cyclonic turning of smaller cloud bands into center.
3. Cirrus blow-off.
4. Major cloudiness to the south of center.

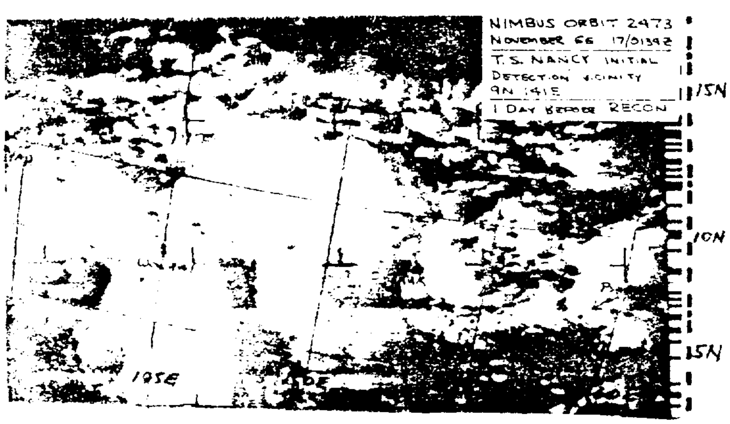


Figure III-15

TYPE 3:

1. Overcast cloud mass forming in ITC.
2. Overcast cloud mass (core).
3. Major cloud mass (bands) to the south of center.
4. Cyclonic turning of cloud bands around center.
5. Shearline approaching center from the north.
6. Cirrus blow-off.

D. AN EXAMPLE OF TWO VORTICES WITHIN A LARGE TROPICAL SYSTEM

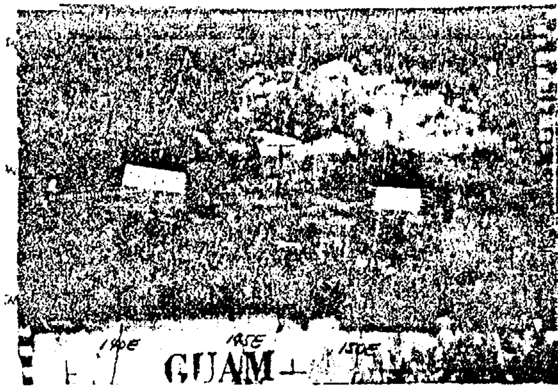
During the two week period of 14 to 28 July, 1967 several interesting aspects of tropical cyclone behavior occurred in the Western Pacific. The period began with an undesignated tropical low forming southwest of Guam in the ITCZ. This low moved northwest through the Ryukyu Islands and into the Yellow Sea, resulting in a break in the subtropical ridge in the Ryukyu Islands area by 20/0000Z. However, the ridge remained strong eastward from Japan. Then followed the development of a large tropical system, which included Tropical Storm DOT and Tropical Depression NINE in the area of Guam, as noted on synoptic charts and APT cloud pictures. The ultimate movement of this system was also toward the northwest, following nearly the same track as that of the previous cyclone into the Yellow Sea.

Between 20/0000Z and 21/0000Z T.S. DOT and T.D. Nine were fixed by reconnaissance aircraft and warnings were issued on the two systems. The two centers began interacting as they moved cyclonically toward one another; T.D. Nine curved from a northerly to a westerly track while DOT moved eastward, figure III-16A.

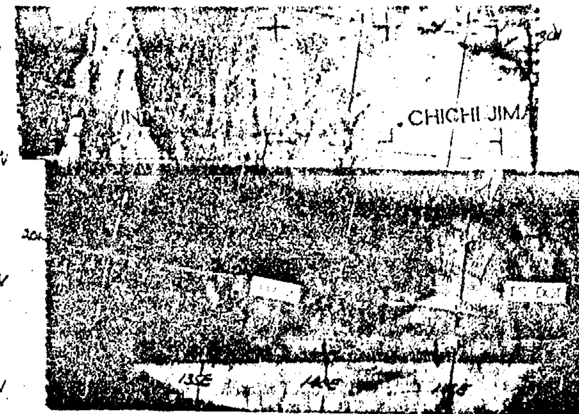
During the period 21/0000Z to 22/0000Z the two centers appeared to undergo a partial Fujiwhara rotation. T.D. Nine, moving westward, passed about 200 miles north of T.S. DOT, while the latter curved toward the north. During this period DOT developed quite rapidly in intensity and became a very large circulation; for example, at 22/0000Z its surface circulation pattern extended 900 miles from north to south and 1100 miles from east to west. DOT's maximum observed surface wind speed reached 50 kts at this time while T.D. Nine remained weak but still had a distinct center as reported by reconnaissance aircraft and as shown by APT pictures, figure III-16B.

By 23/0000Z T.D. Nine became absorbed into the large circulation of T.S. DOT. DOT's circulation remained very large through 25 July as indicated by satellite pictures, reconnaissance data, and surface reports, figure III-16C.

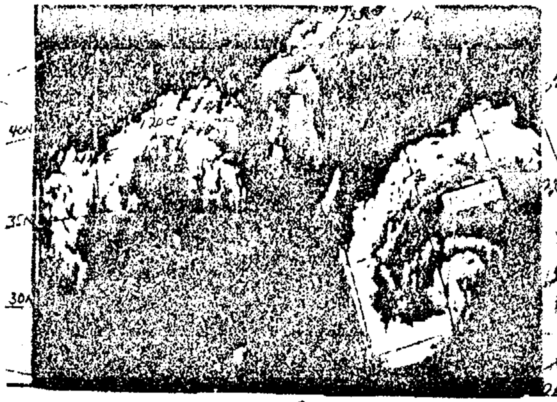
Throughout the period 22 to 26 July the remnants of T.D. Nine appeared to track along as a secondary center in DOT's circulation. Because of the large size of the overall circulation, the relative weakness of the storm, and the presence of the secondary center, this was a difficult period for both the forecasters and the reconnaissance missions. It was decided that the most meaningful "best track" for this period, as determined from post-analysis, would be the track of the geographical center of the overall circulation. As can be seen from the fix positions for DOT, the most consistently fixed center, and apparently the most intense, was that to the north of the mean track, while a second center, the remnant of T.D. Nine, followed along to the south, figure III-16D. As DOT passed southern Japan its center became well-defined, the circulation became much smaller, and it reached its greatest intensity. After this, DOT was fixed consistently as one distinct center as it followed a northwesterly track into the Yellow Sea where it became extratropical.



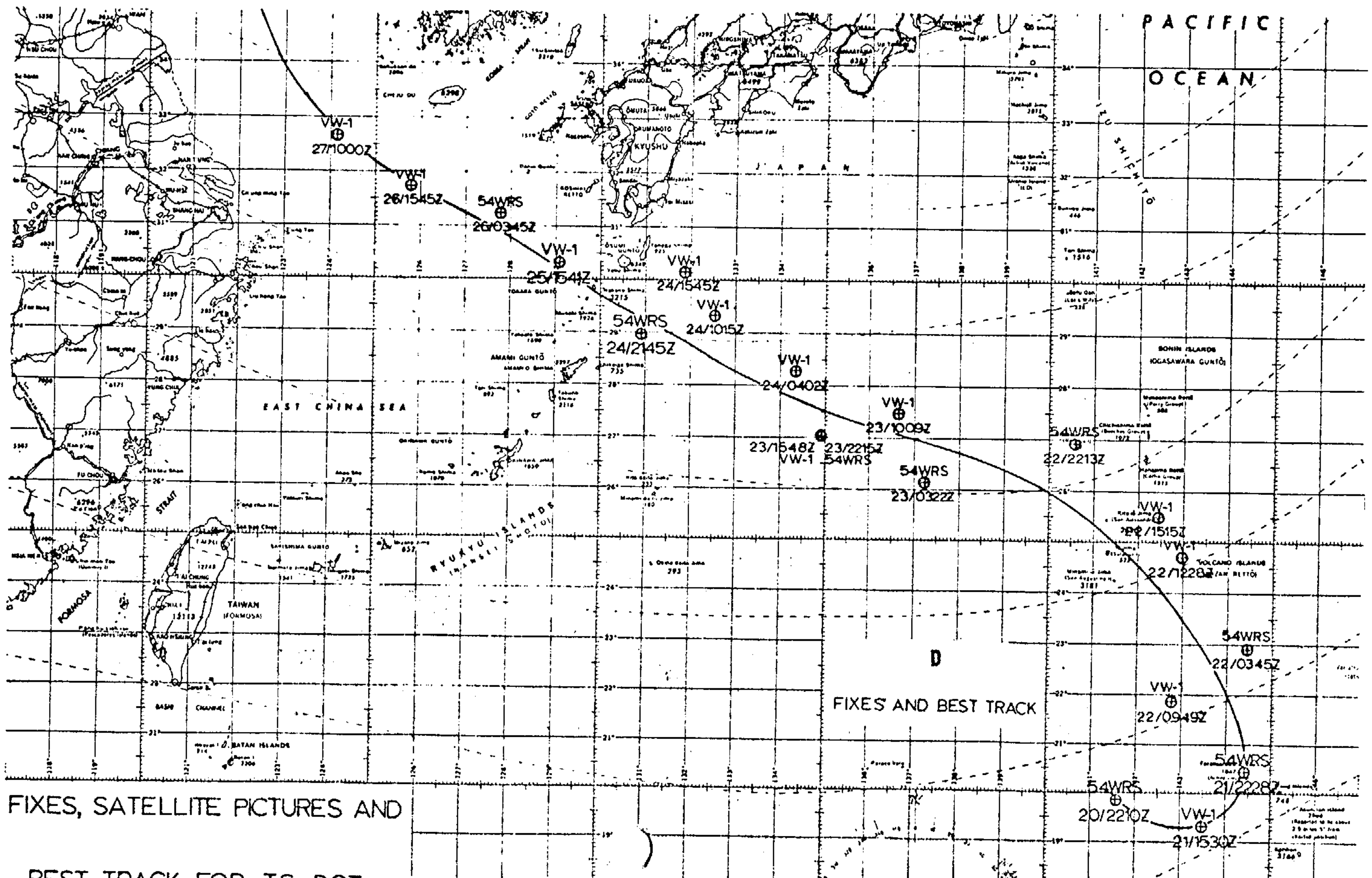
A
NIMBUS 20/0136Z
JULY 1967



B
NIMBUS 22/0226Z
JULY 1967



C
ESSA II 23/2316Z
JULY 1967



D
FIXES AND BEST TRACK

FIXES, SATELLITE PICTURES AND

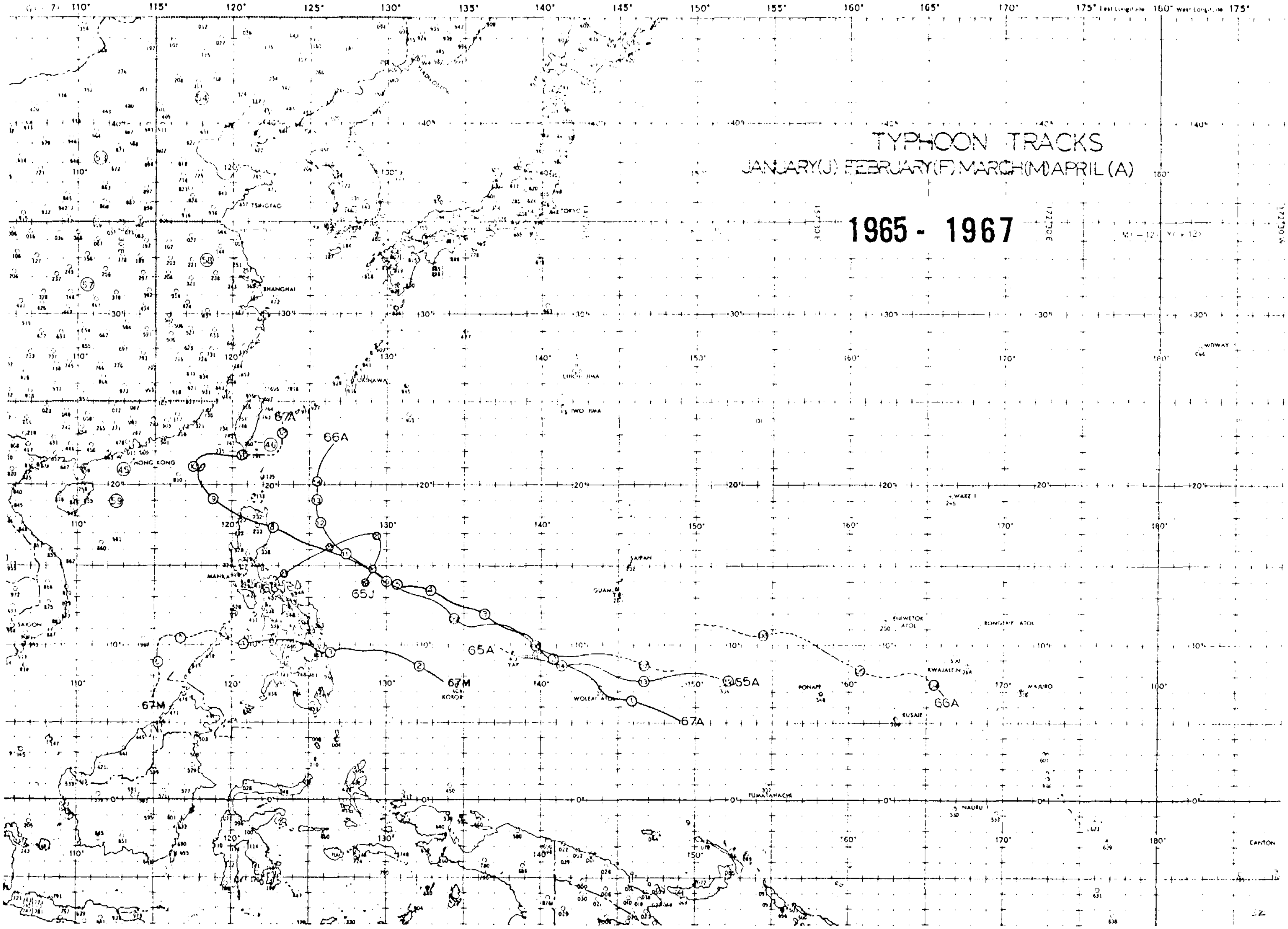
BEST TRACK FOR T.S. DOT

Figure III-16

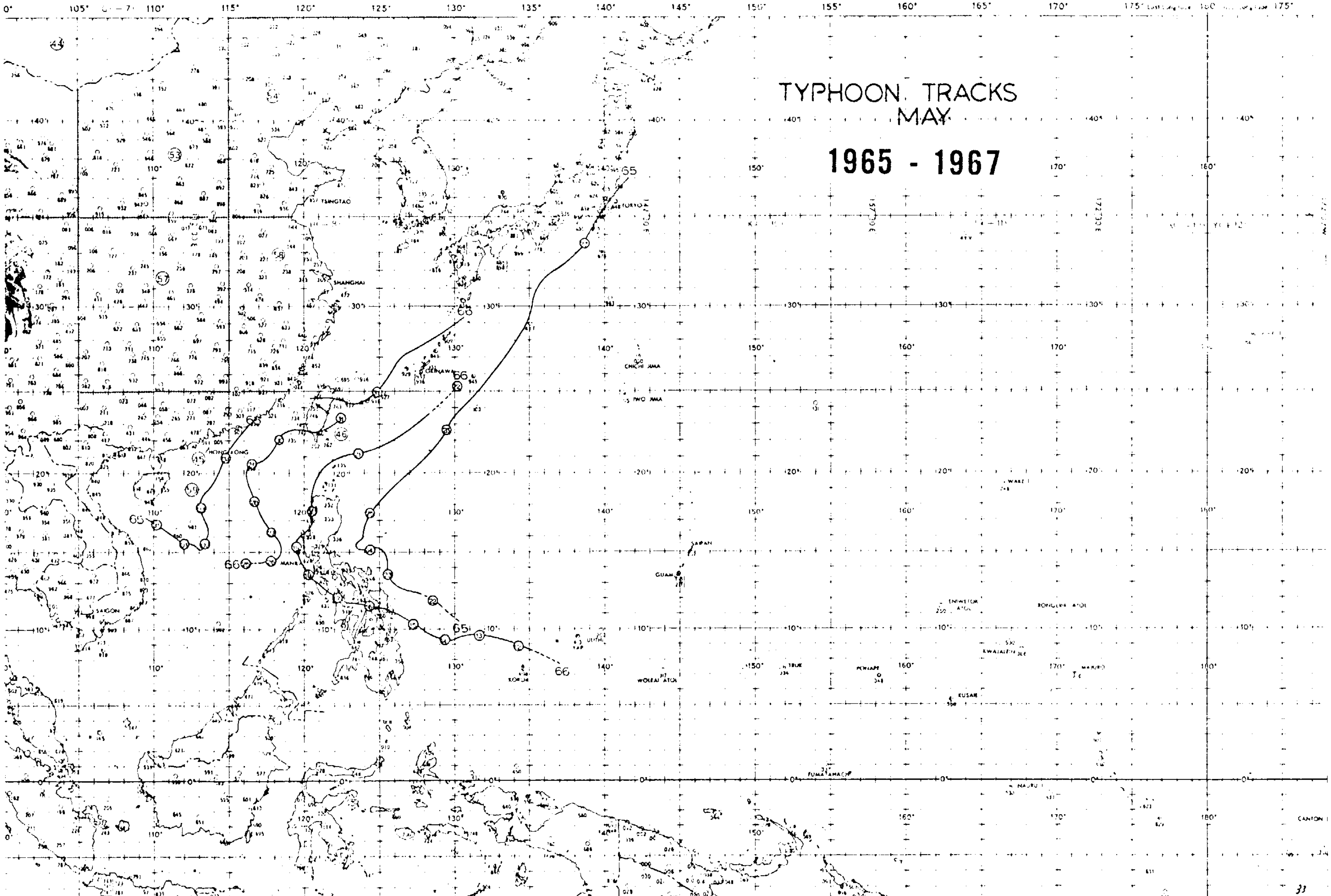
TYPHOON TRACKS

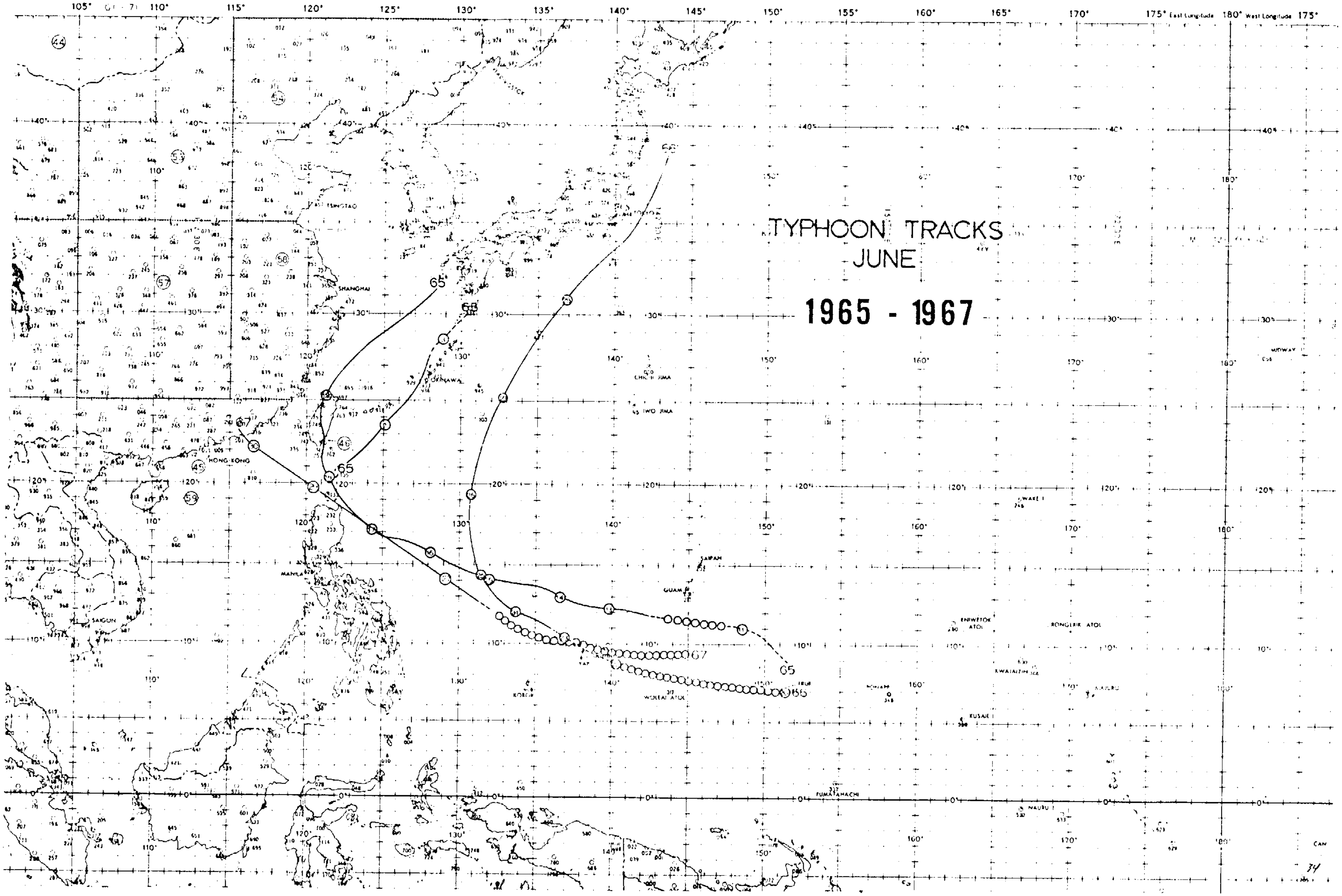
1965 - 1967

Tracks for the 1965-1967 seasons are included in this report. For all tracks, by month, prior to 1965 see prior Typhoon Reports.

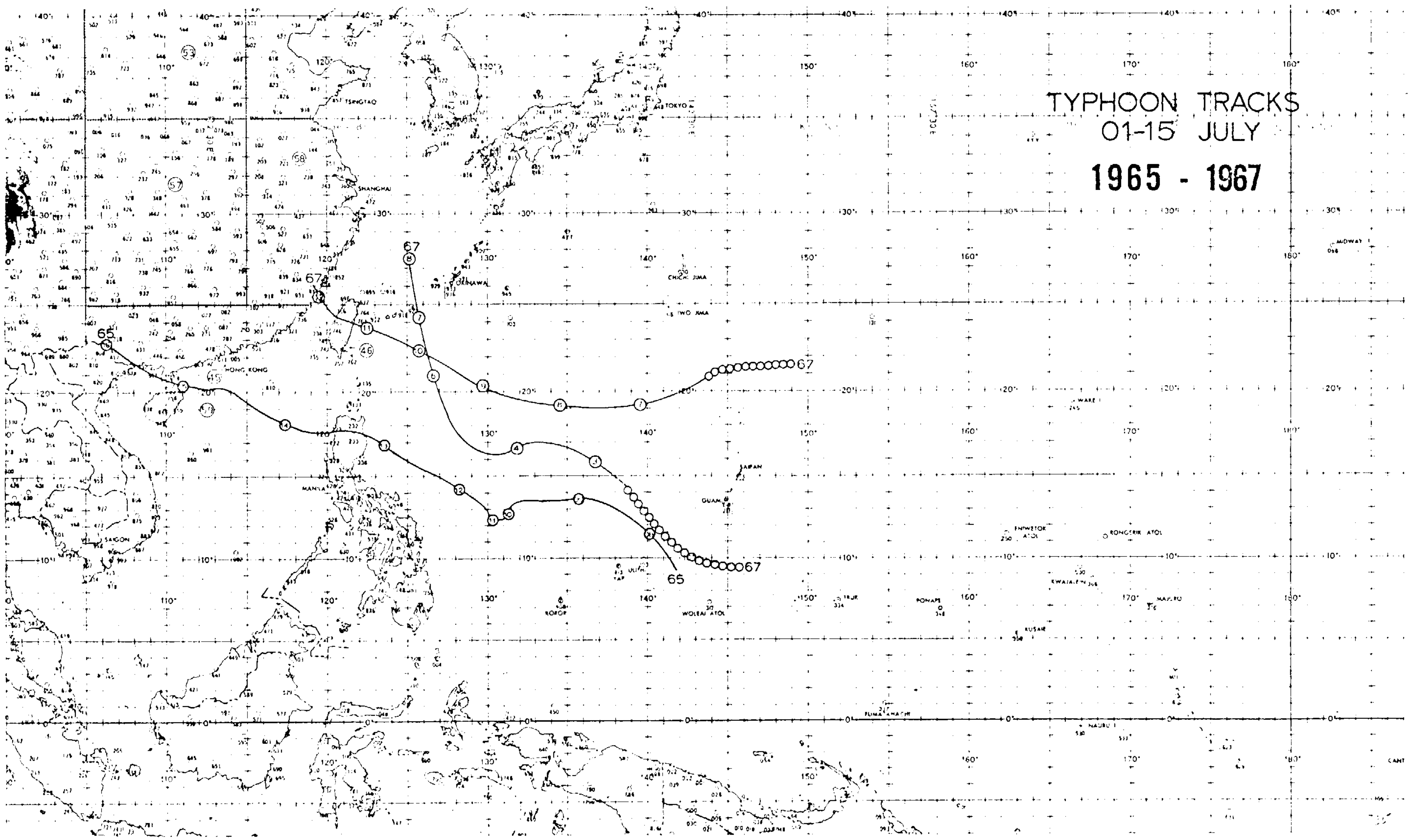

TYPHOON TRACKS
JANUARY(J) FEBRUARY(F) MARCH(M) APRIL (A)
1965 - 1967
65J
65A
66A
67A
67M
HONG KONG
SHANGHAI
MANILA
SAIGON
GUAM
SAIPAN
IWO JIMA
WAKE I
ENIWETOK ATOLL
KWAJALEIN
PONAPE
KUSAIE
MAJURO
WOLEAI ATOLL
KOROR
YAP
MIDWAY I
NAURU I
CANTON

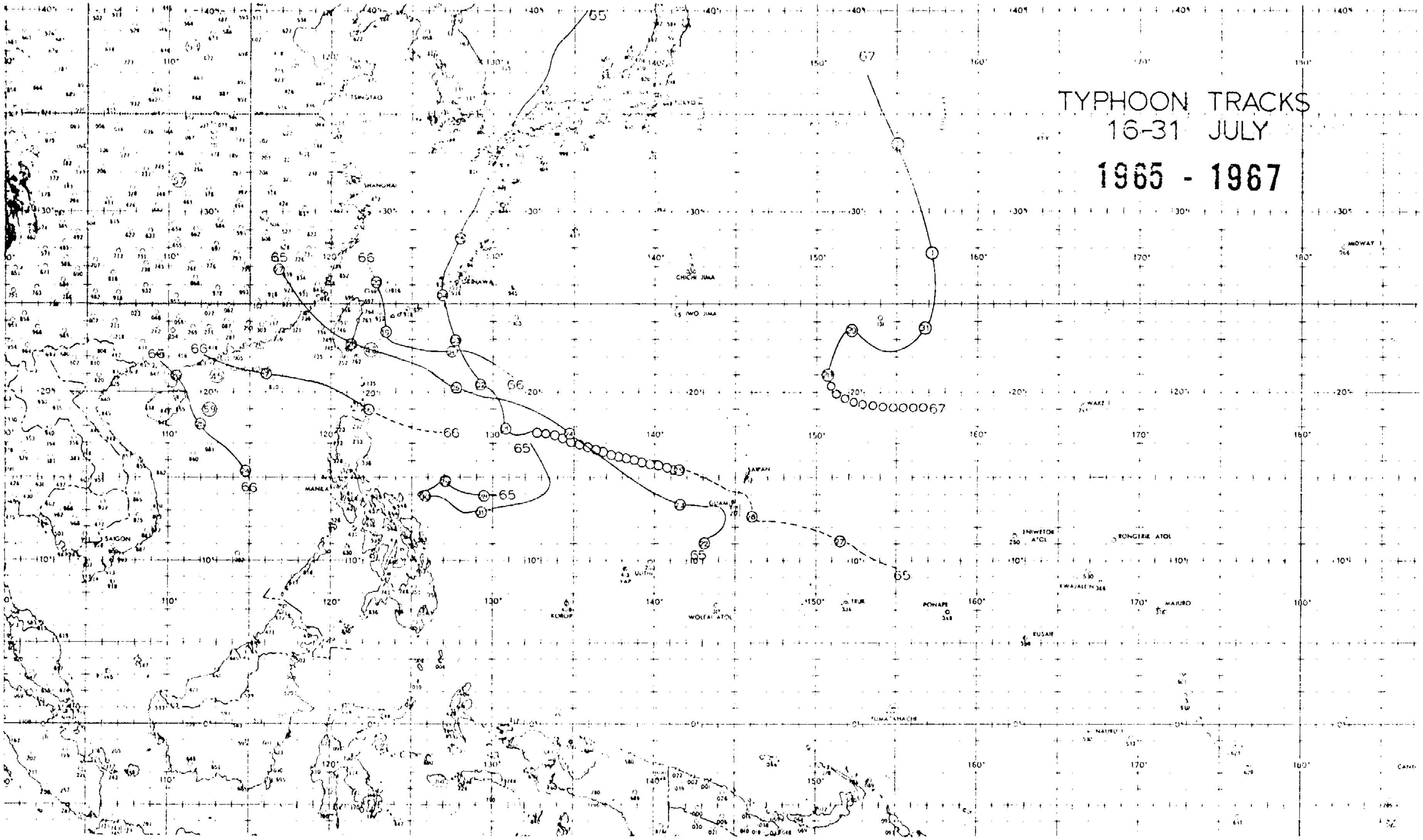
TYPHOON TRACKS
MAY
1965 - 1967

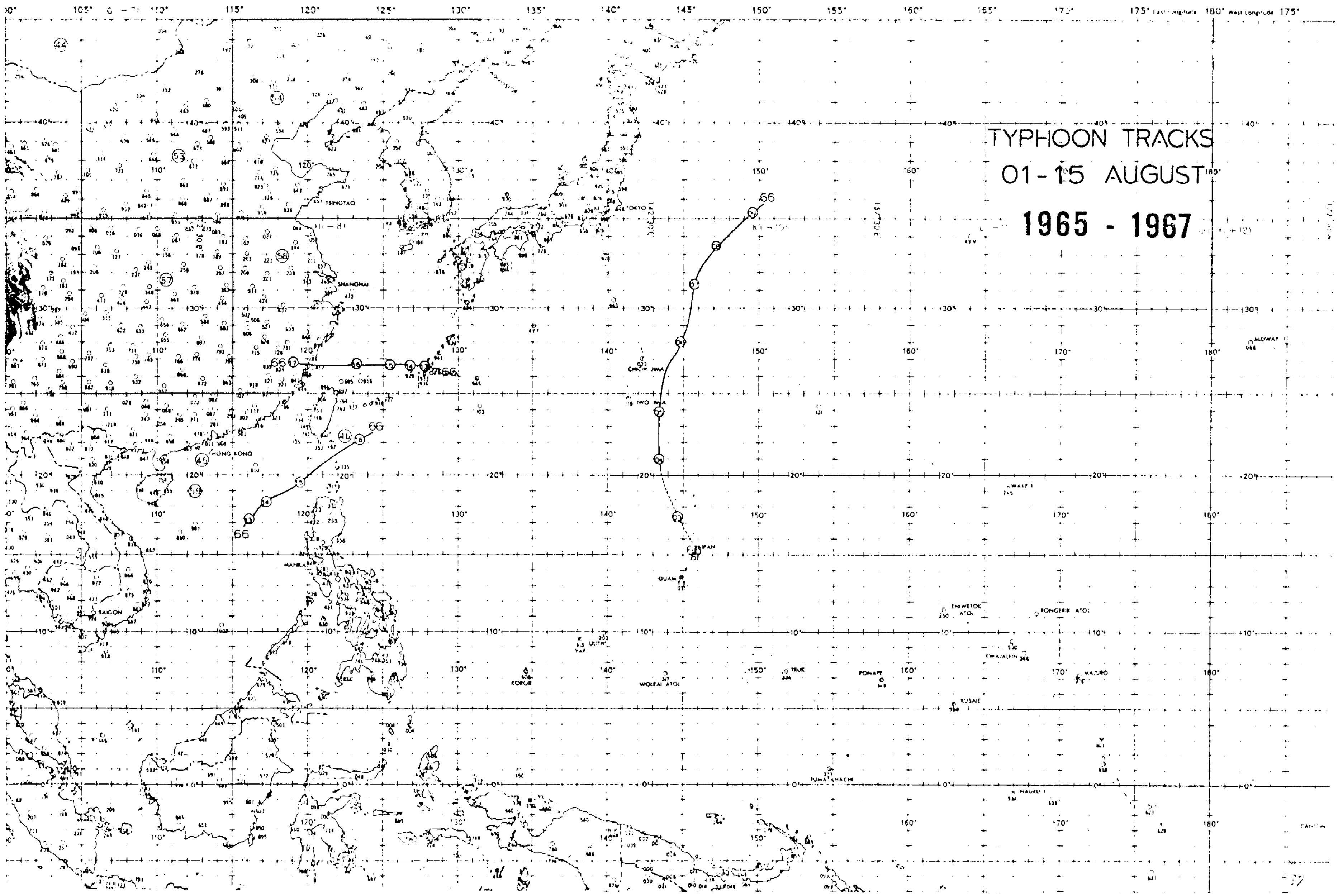


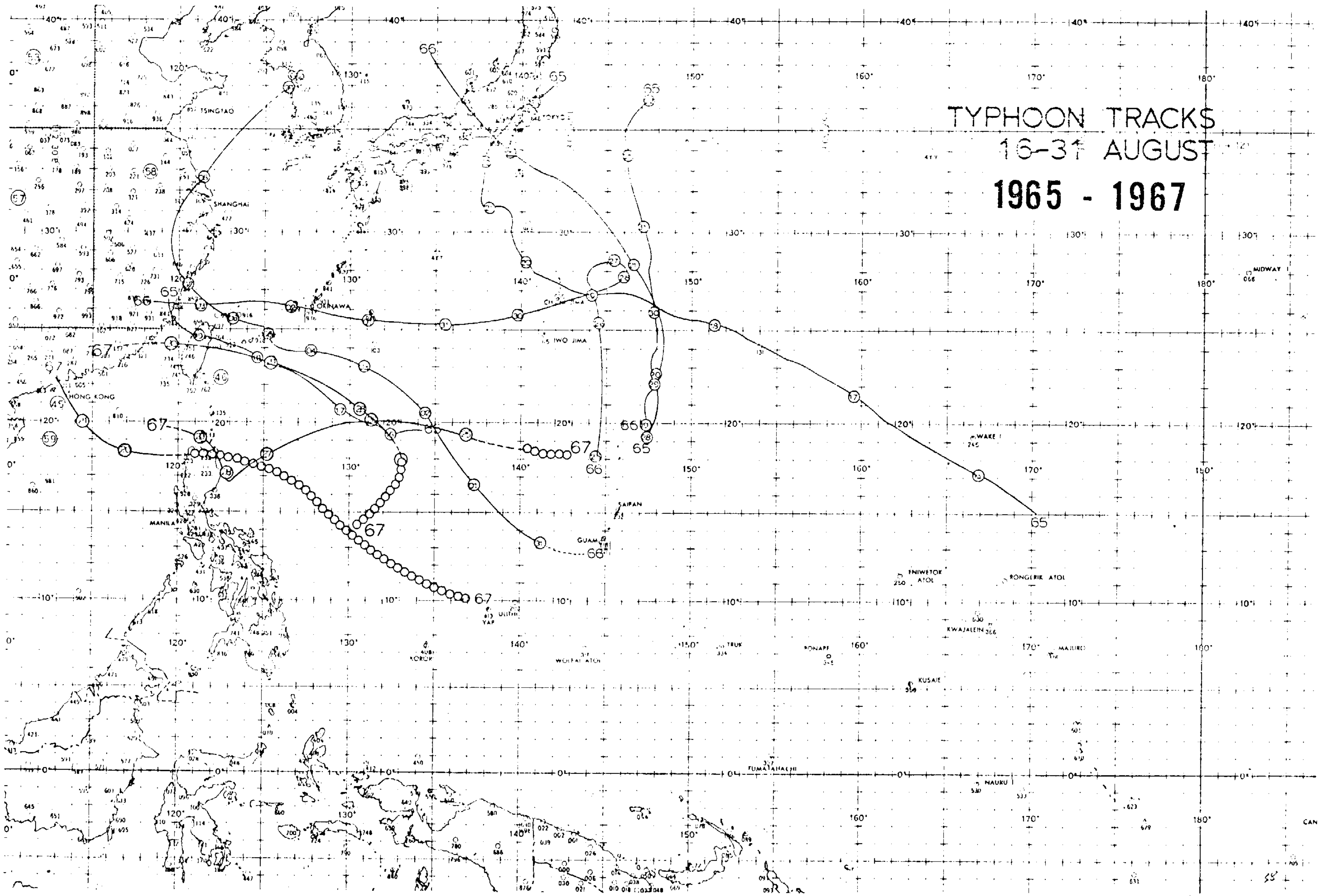


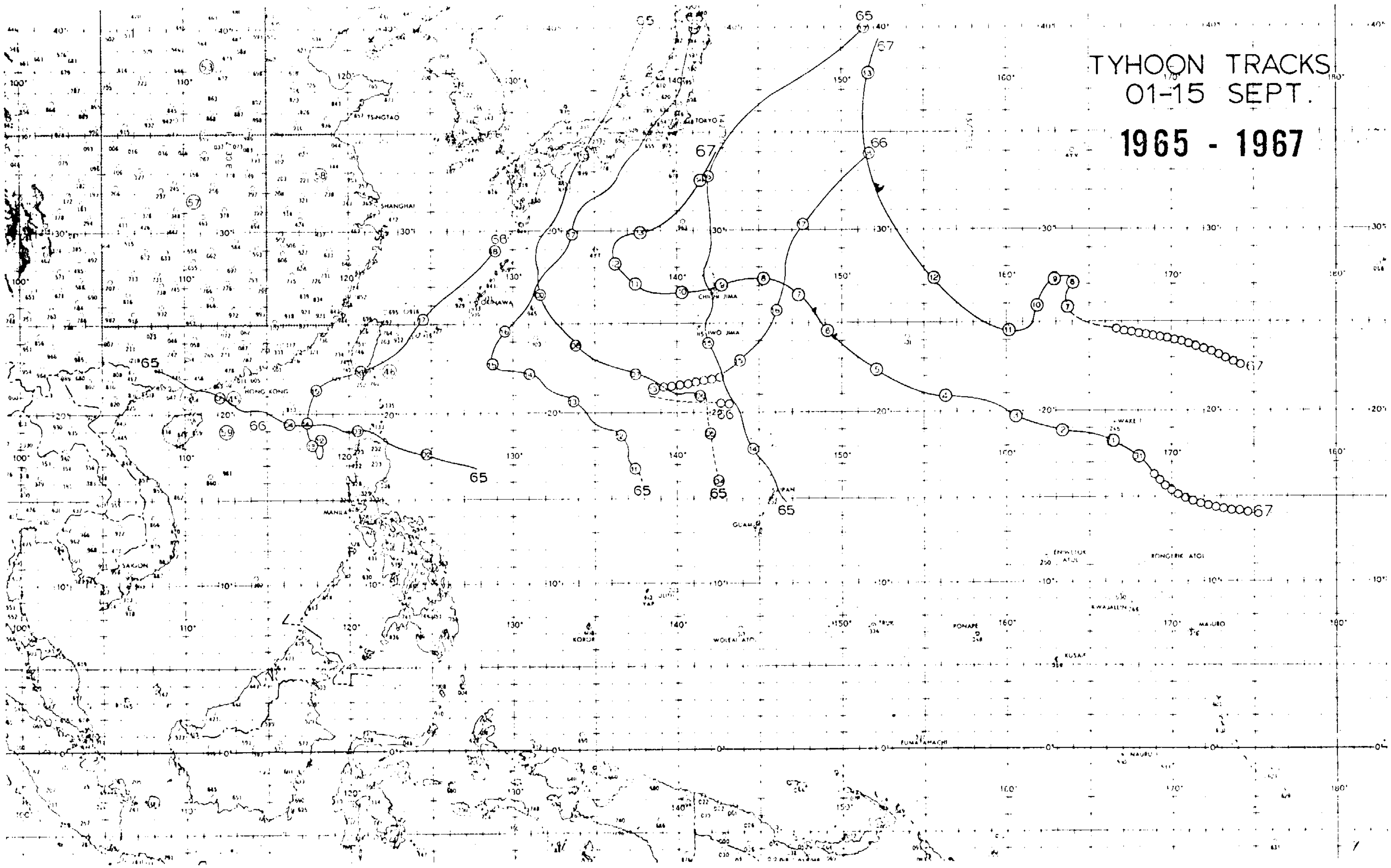
TYPHOON TRACKS
JUNE
1965 - 1967
SHANGHAI
TSINGTAO
HONG KONG
MANILA
SAIGON
OKINAWA
IWO JIMA
GUAM
SAIPAN
WAKE I

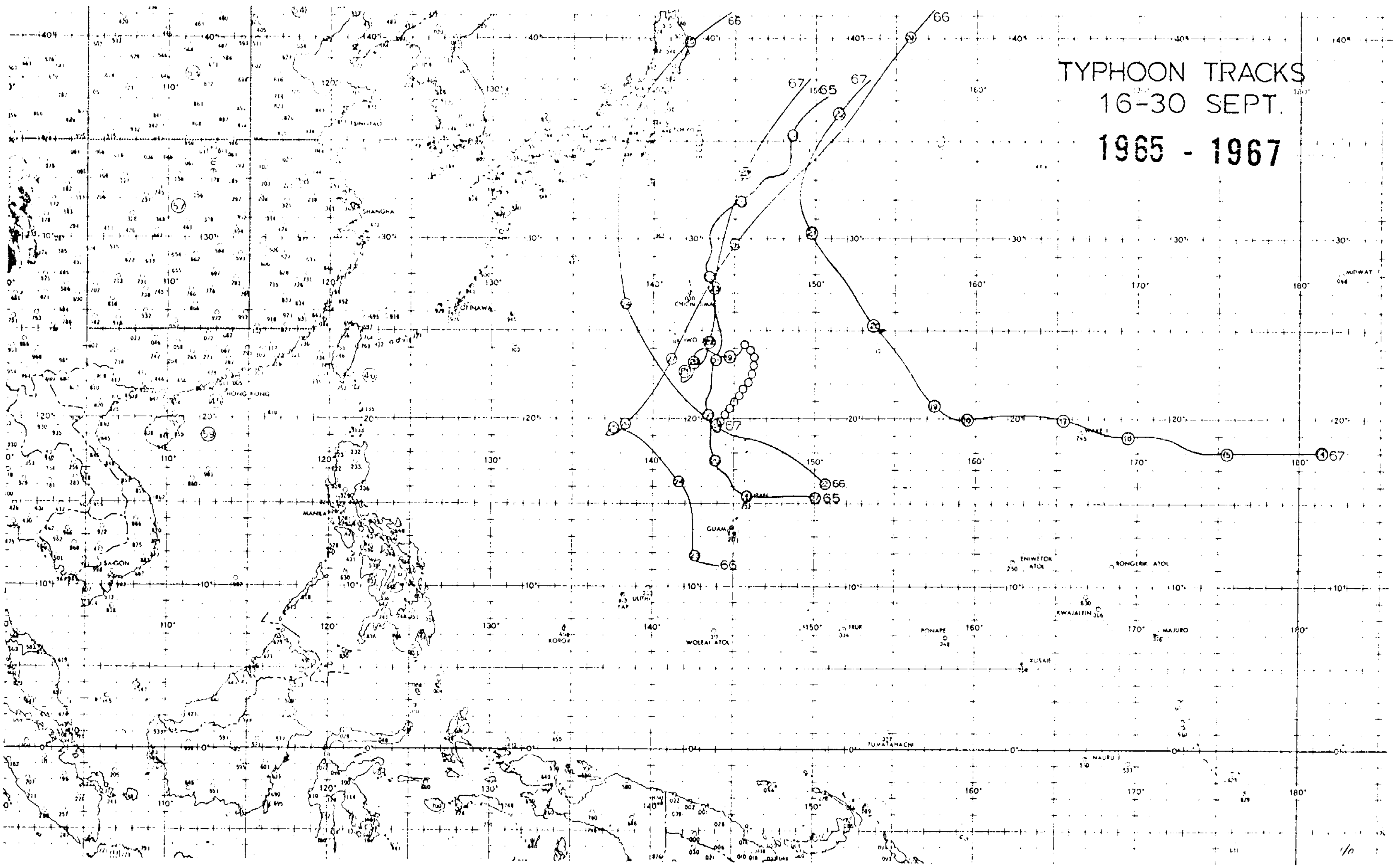

TYPHOON TRACKS
01-15 JULY
1965 - 1967
65
67
HONG KONG
SHANGHAI
MANILA
SAIGON
OKINAWA
GUAM

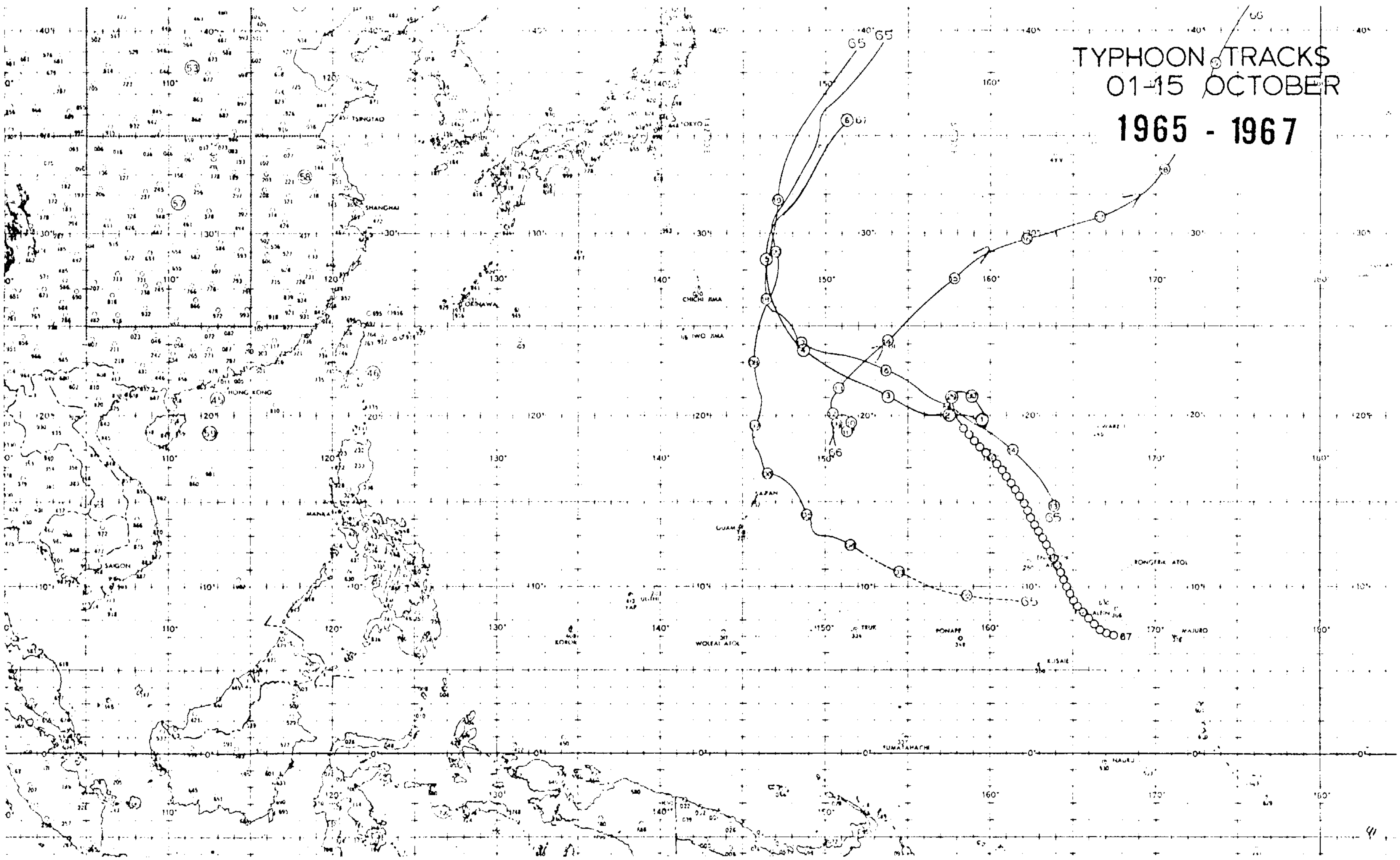

TYPHOON TRACKS
16-31 JULY
1965 - 1967
MANILA
SAIGON
SHANGHAI
GUAM
SAIPAN
WAKE I
PONAPE
MAJURO
KUSAIE
TRUK
YAP
ULITHI
KOROR
WOLEAI ATOLL
CHICHI JIMA
IWO JIMA
OKINAWA
ENIWETOK ATOL
KWAJALEIN
MIDWAY I

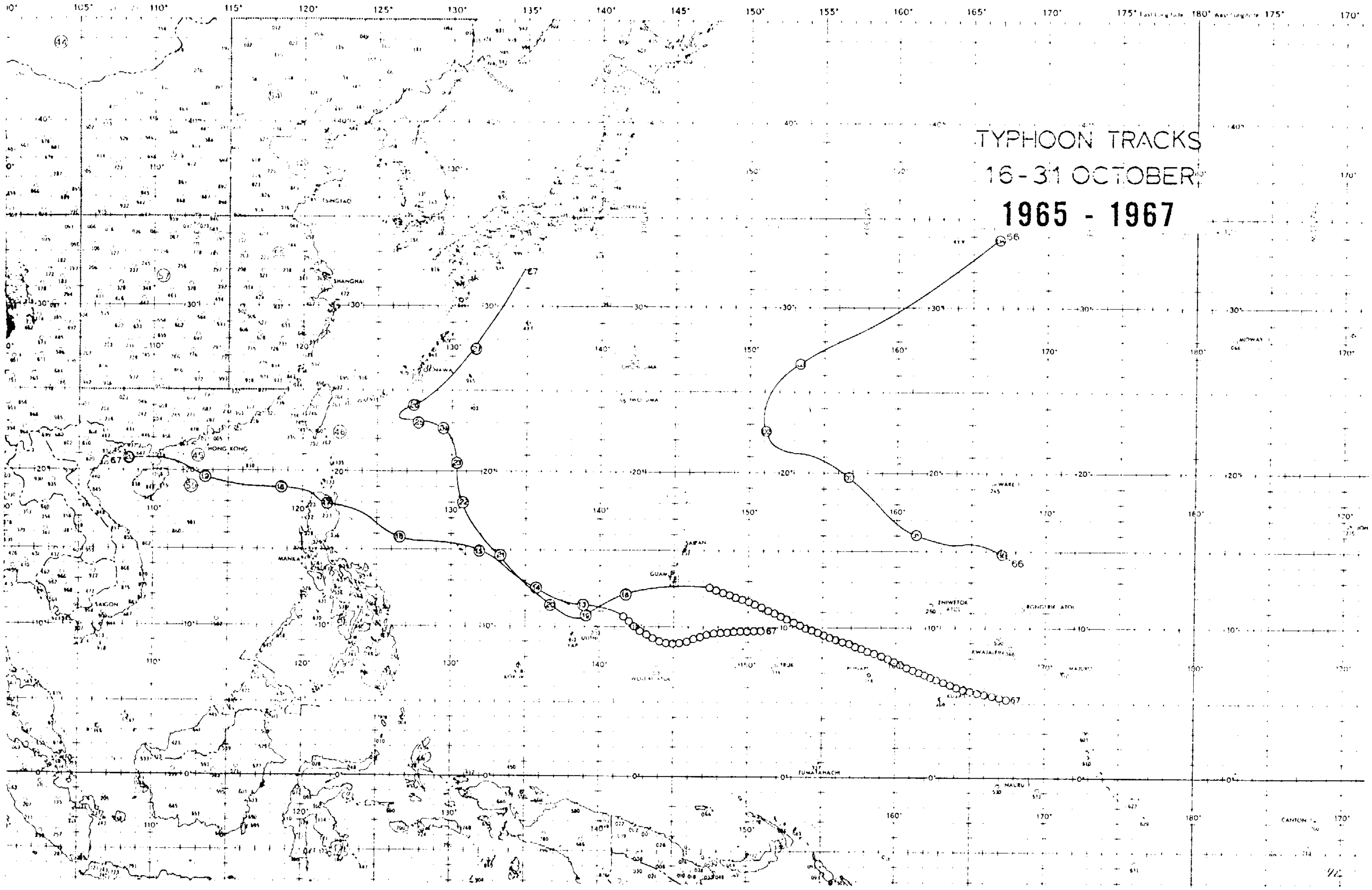

TYPHOON TRACKS
01-15 AUGUST
1965 - 1967
TOKYO
SHANGHAI
TSINGTAO
HONG KONG
MANILA
SAIGON
CHICHI JIMA
IWO JIMA
SAIPAN
GUAM
WAKE I
MIDWAY I
ENIWETOK ATOL
RONGERIK ATOL
KWAJALEIN
MAJURO
KUSAIE
PONAPE
TRUK
WOLEAI ATOL
KORORI
ULITHI
YAP
NAURU I
CANTON

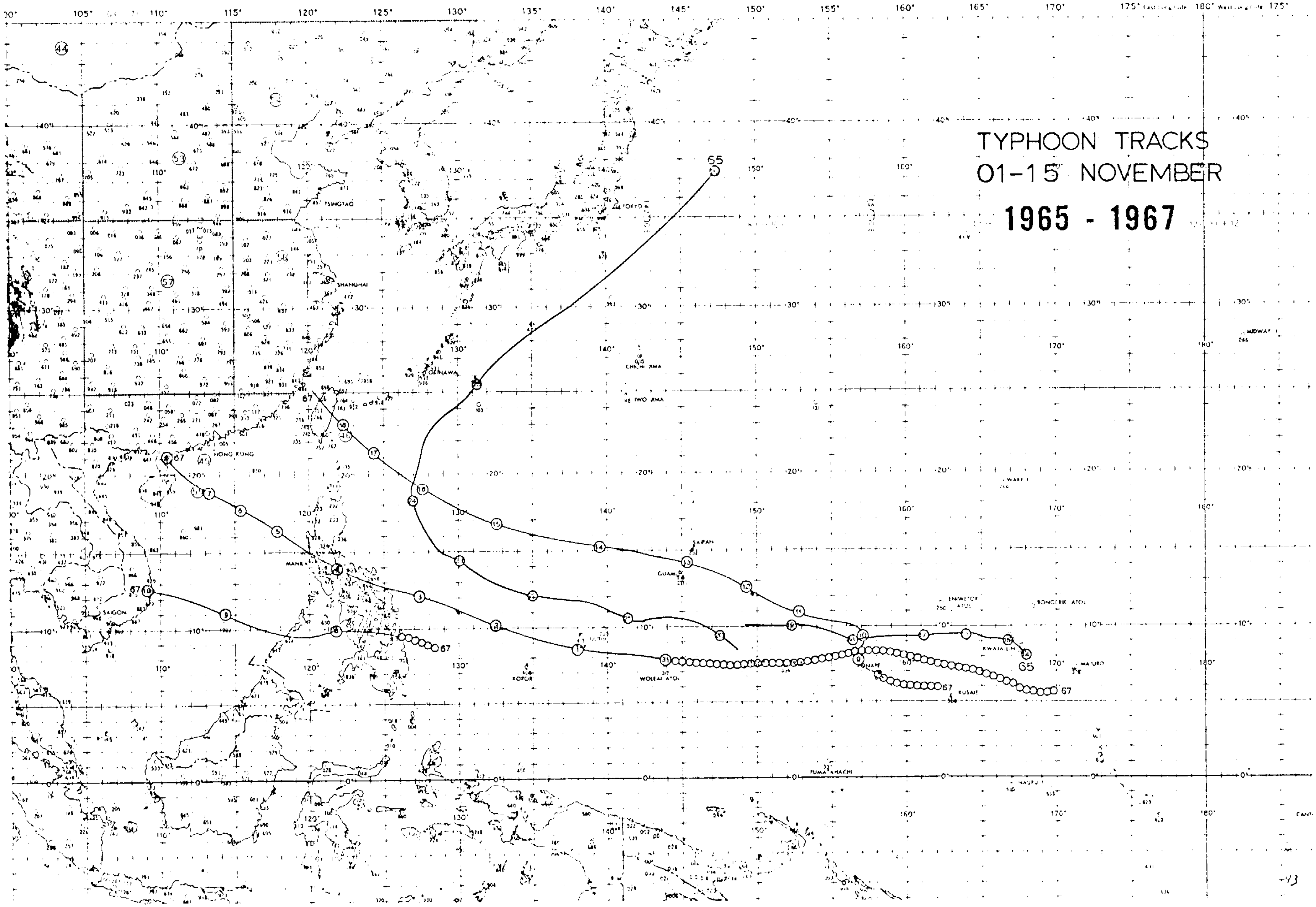

TYPHOON TRACKS
16-31 AUGUST
1965 - 1967
TSINGTAO
SHANGHAI
OKINAWA
HONG KONG
MANILA
IWO JIMA
SAIPAN
GUAM
WAKE I
MIDWAY
ENIWETOK ATOL
RONGERIK ATOL
KWAJALEIN
MAJURO
PONAPE
TRUK
KUSAIE
NAURU
YAP
ULITHI
KOROR
WOLEAI ATOL
TOKYO


TYHOON TRACKS
01-15 SEPT.
1965 - 1967

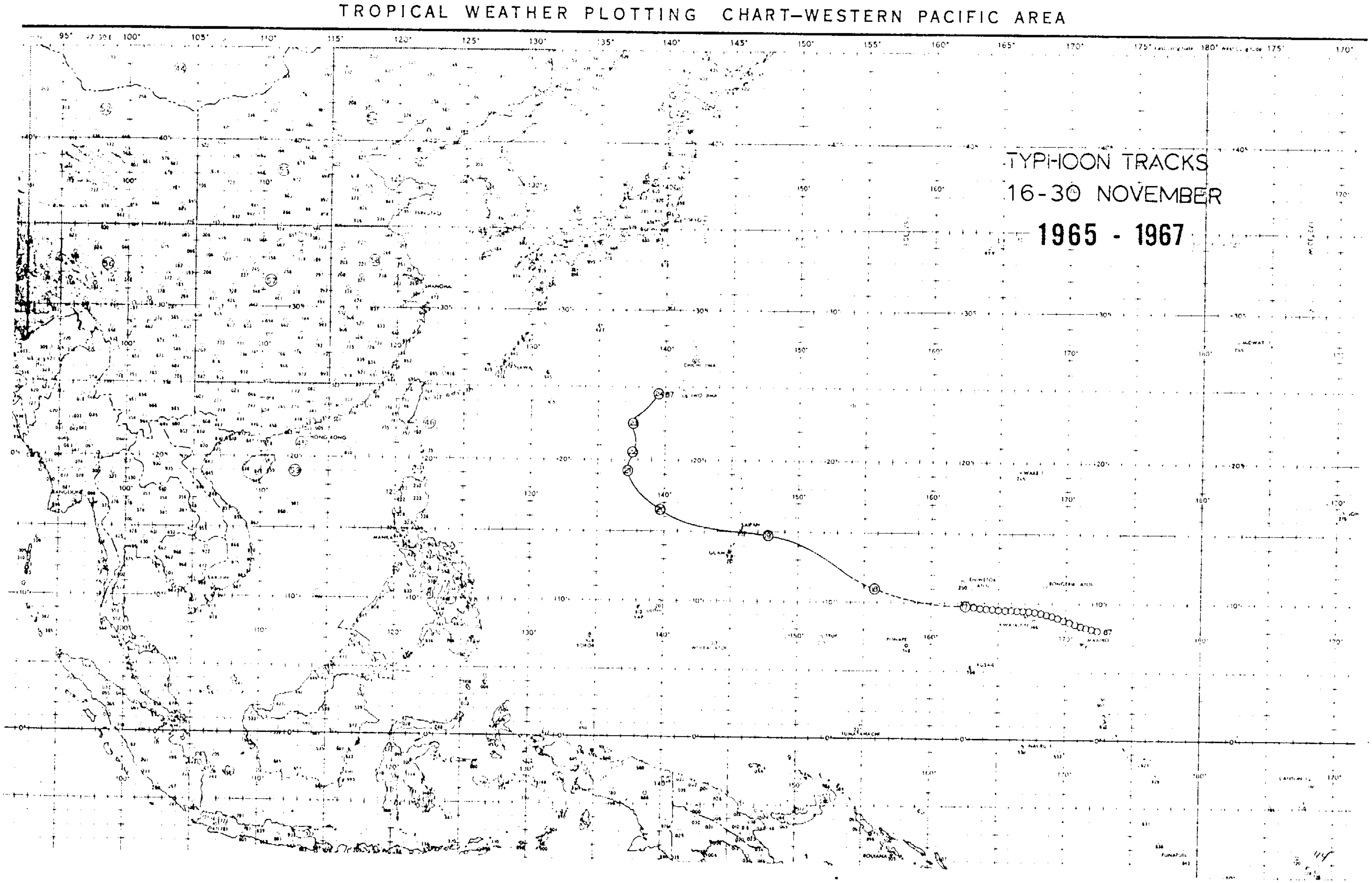

TYPHOON TRACKS
16-30 SEPT.
1965 - 1967

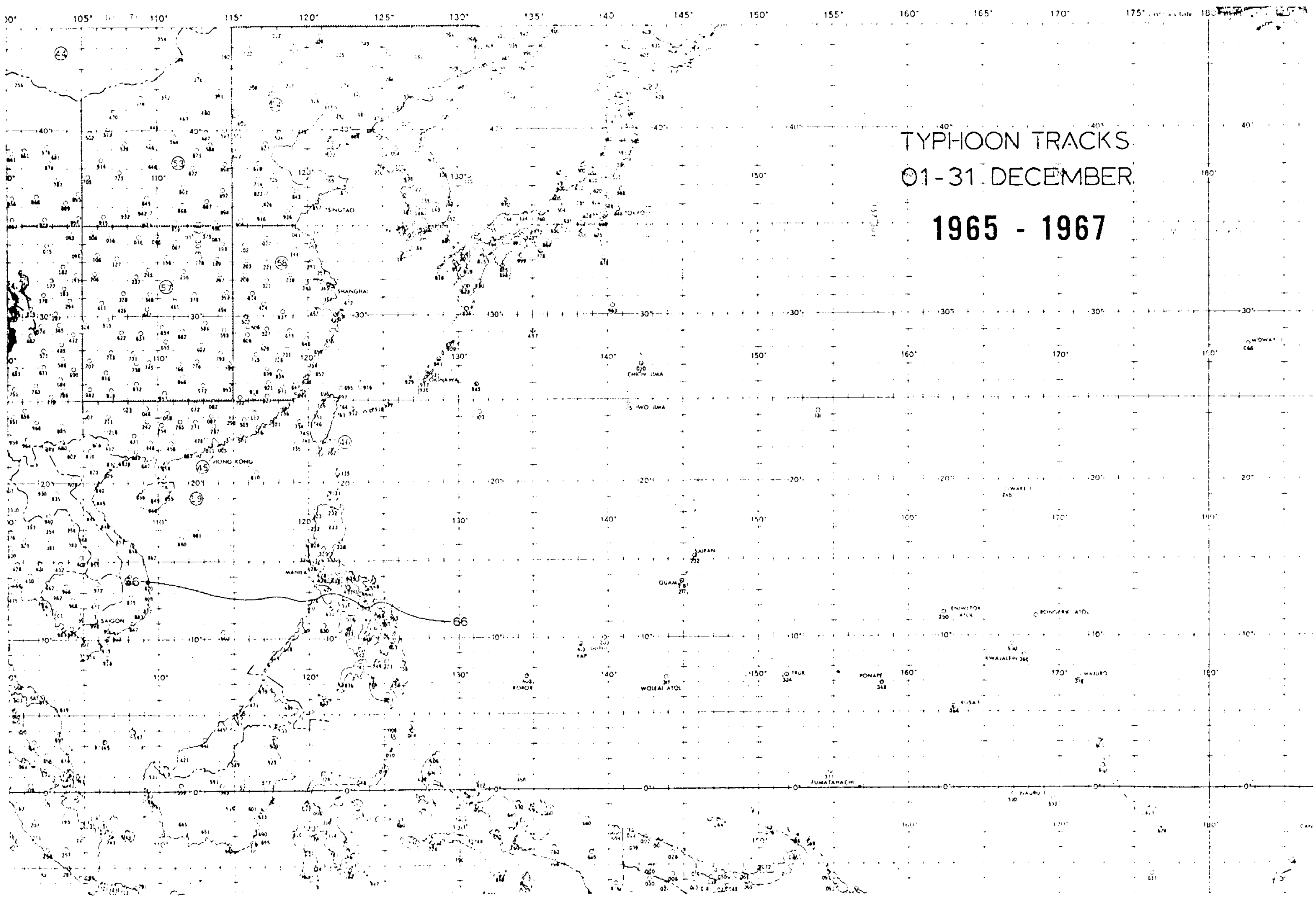

TYPHOON TRACKS
01-15 OCTOBER
1965 - 1967
TSINGTAO
SHANGHAI
TOKYO
HONG KONG
OKINAWA
CHICHI JIMA
IWO JIMA
MANILA
SAIGON
SAIPAN
GUAM
TRUK
PONAPE
WOLEAI ATOL
KOROR
MAJURO
RONGERIK ATOL


TYPHOON TRACKS
16 - 31 OCTOBER
1965 - 1967
SHANGHAI
HONG KONG
SAIGON
GUAM
SAIPAN



TYPHOON TRACKS
01-15 NOVEMBER
1965 - 1967
HONG KONG
SHANGHAI
TSINGTAO
SAIGON
OKINAWA
GUAM
SAIPAN
IWO JIMA
CHICHI JIMA
TOKYO
KWAJALEIN


TROPICAL WEATHER PLOTTING CHART—WESTERN PACIFIC AREA
TYPHOON TRACKS
16-30 NOVEMBER
1965 - 1967


TYPHOON TRACKS
01-31 DECEMBER
1965 - 1967
SHANGHAI
HONG KONG
MANILA
SAIGON
OKINAWA
TOKYO
SAIPAN
GUAM
66

[redacted]

TYPHOON FREQUENCY
10 YEAR PERIOD

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL TOTAL
1958	1	0	0	0	1	2	5	3	3	3	1	1	20
1959	0	0	0	1	0	0	1	5	3	3	2	2	17
1960	0	0	0	1	0	2	2	8	0	4	1	1	19
1961	0	0	1	0	2	1	3	3	5	3	1	1	20
1962	0	0	0	1	2	0	5	7	2	4	3	0	24
1963	0	0	0	1	1	2	3	3	3	4	0	2	19
1964	0	0	0	0	2	2	6	3	5	3	4	1	26
1965	1	0	0	1	2	2	4	3	5	2	1	0	21
1966	0	0	0	1	2	1	3	6	4	2	0	1	20
1967	0	0	1	1	0	1	3	4	4	3	3	0	20
AVE	.2	0	.2	.7	1.2	1.3	3.5	4.5	3.4	3.1	1.6	.9	20.6